

REINHOLD ENVIRONMENTAL Ltd.



## **2017 NO<sub>x</sub>-Combustion-CCR Round Table Presentation**

February 27 & 28, 2017, in Cleveland, OH / Hosted by FirstEnergy

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# Geotechnical Investigation and Evaluations for Closing CCR Impoundments

2017 NOx – Combustion – CCR  
Roundtable/PCUG Meeting

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February 27, 2017

# CCR Impoundment Closure

- CCR Rule (2015) requires existing unlined impoundments to retrofit or close:
  - If location restrictions are not met.
  - If factor of safety requirements are not met.
  - If ground water monitoring requirements are not met.

# CCR Impoundment Closure Options

- Clean Closure
  - CCR removal
  - Decontaminate areas affected by CCR impoundment releases.
- Closure leaving CCR in-place
  - Final cover system
  - Alternate cover system
  - Stabilize in place and cover
  - Conversion to dry disposal – CCR landfill
- Focusing on in-place closure of CCR

# CCR Impoundment Closure Plan Design

- Develop and implement a comprehensive geotechnical investigation program
- Collect in-situ field data and high quality undisturbed samples for:
  - Laboratory testing
  - Material characterization
- Perform engineering analyses to address
  - Slope Stability
  - Settlement
  - Liquefaction
- Meet new CCR Rule requirements

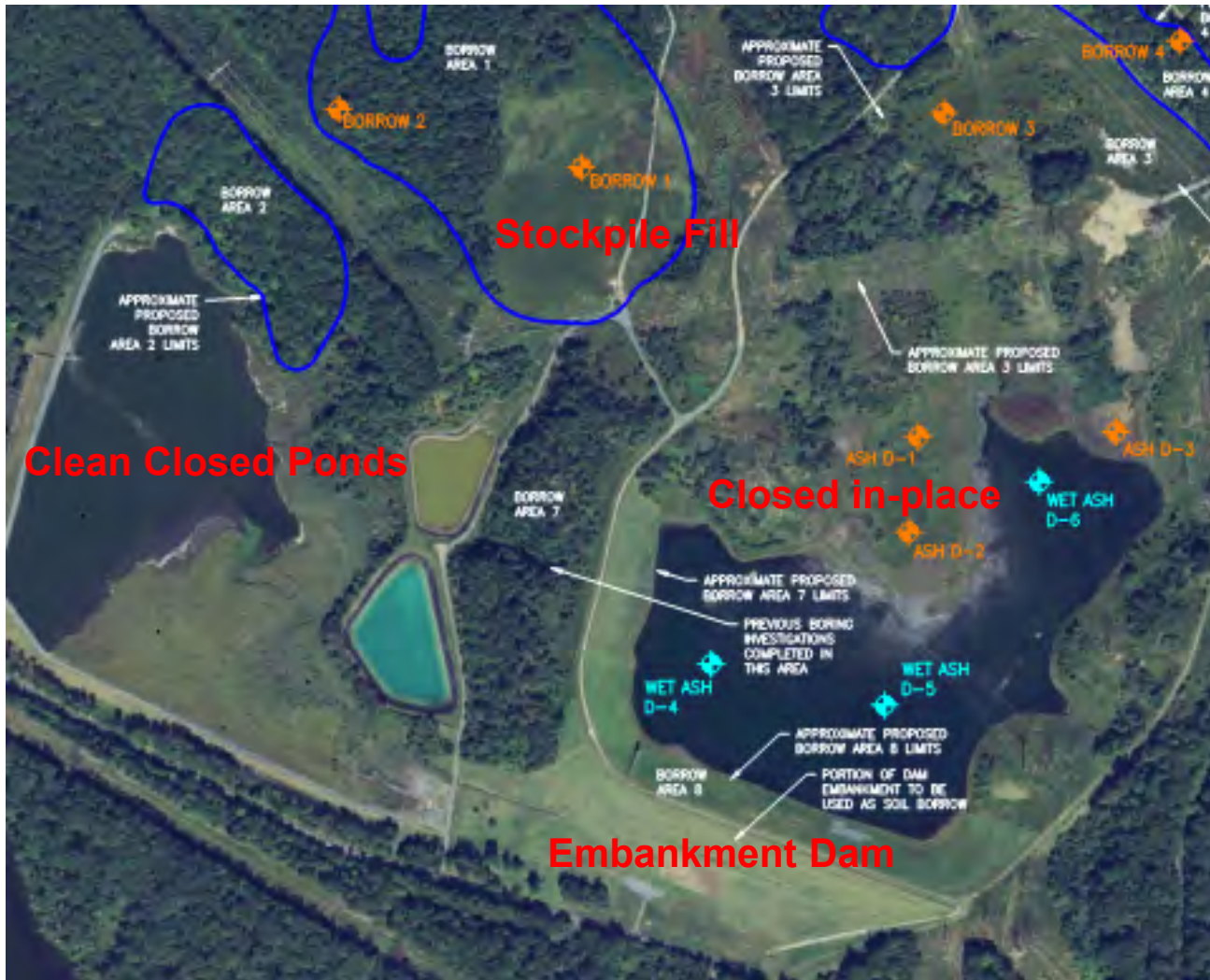
# Benefits of Robust Geotechnical Investigation

- Characterize ash and soil materials within the impoundment, embankment, and foundation.
  - Yields supporting data for development of realistic engineering properties.
  - Optimizes static and seismic analyses.
  - Minimizes uncertainty and risk.

# Discussion Topics

1. Field testing methods
2. Typical minimum laboratory testing
3. Material characterization
4. Applicable CCR Rule requirements
5. Deep-seated stability
6. Settlement
7. Final cover system/veneer stability
8. Liquefaction and seismic stability

# Field Testing - Typical Boring Location Plan



# CCR Field Testing Methods

- Field Testing method:
  1. Piezo-Seismic Cone Penetration Testing (PS-CPT)
- Ideal in hydraulically-placed materials.
- Performed in-situ, and measures tip stress, sleeve stress (friction) and pore pressure.
- Should also include performing:
  - Shear wave velocity testing to correlate dynamic properties; and,
  - Pore pressure dissipation tests to estimate permeability.

# CCR Field Testing Methods

**CME75 Drill Rig**

**30-Ton PS-CPT Rig**



## CCR Field Testing Methods

- CPT is very repeatable and efficient means of collecting continuous subsurface data.
- Less affected by equipment and operator variability.
- Well-suited in soft, saturated ash within an impoundment.
- CPT data correlate static and seismic geotechnical parameters and material characterizations.
- Pore pressure dissipation data correlate permeability and coefficient of consolidation.

# CCR Field Testing Methods



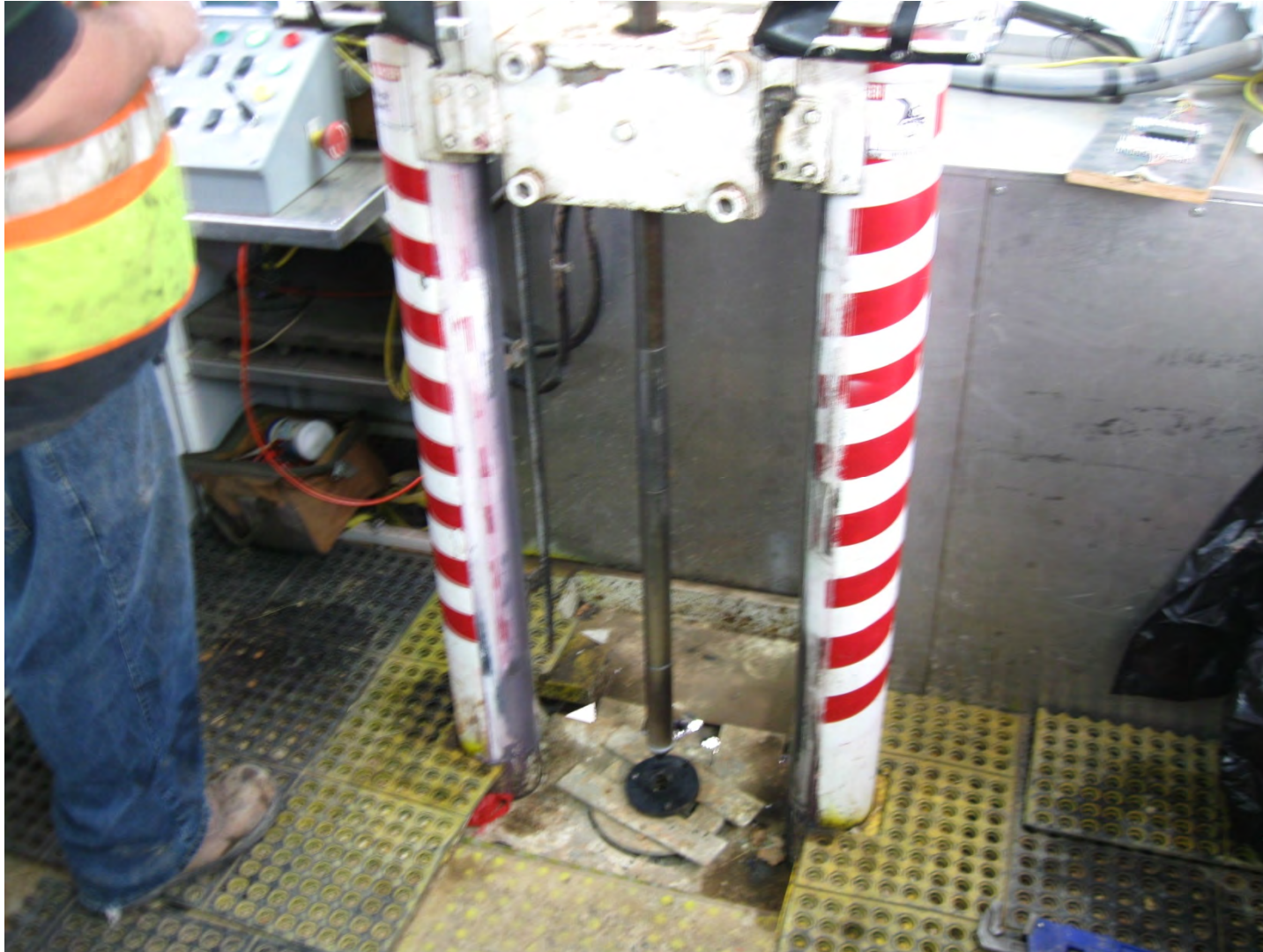
# CCR Field Testing Methods - PSCPT



# CCR Field Testing Methods - PSCPT



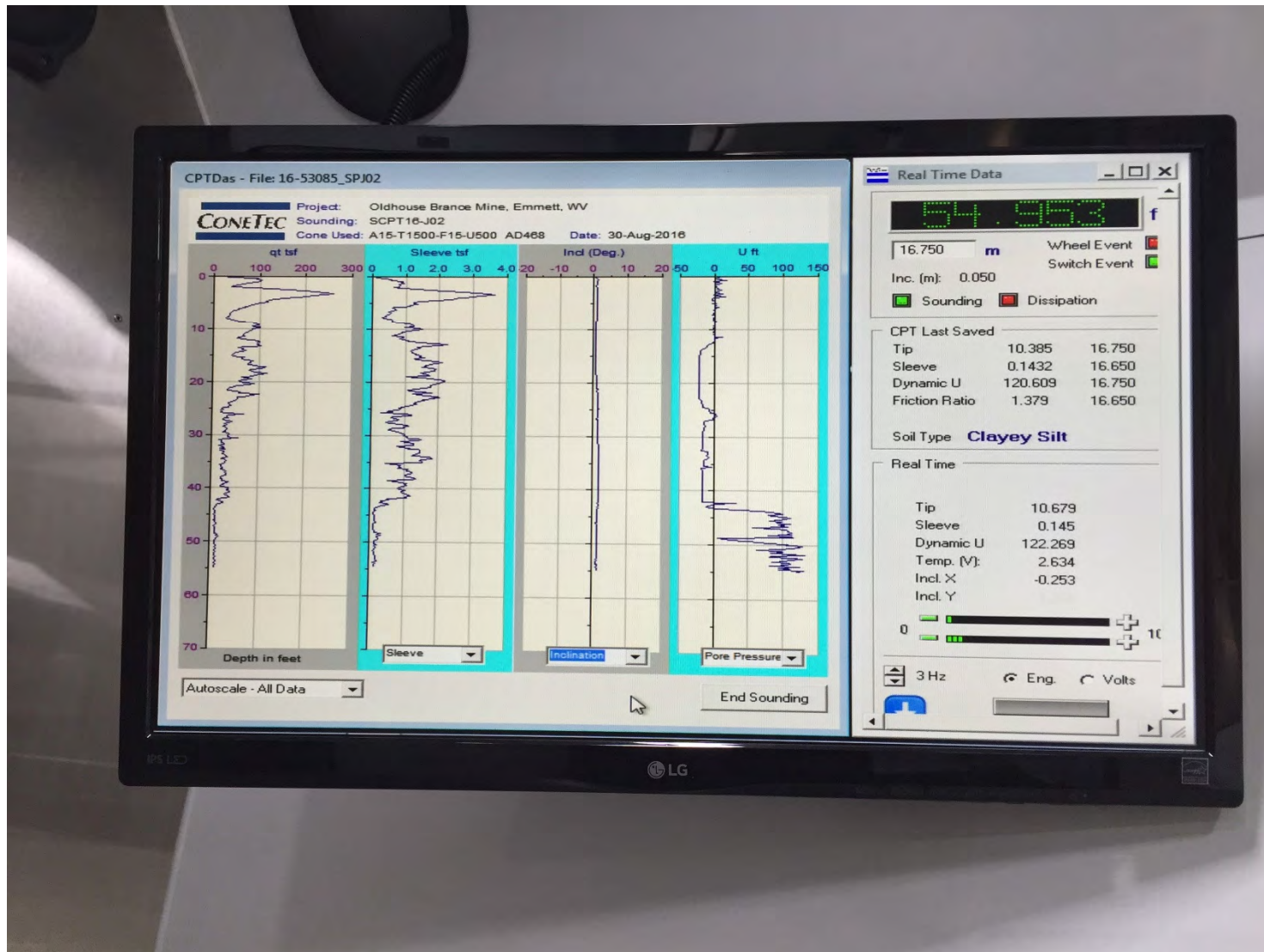
# CCR Field Testing Techniques - PSCPT



# CCR Field Testing Methods – Seismic Hammer

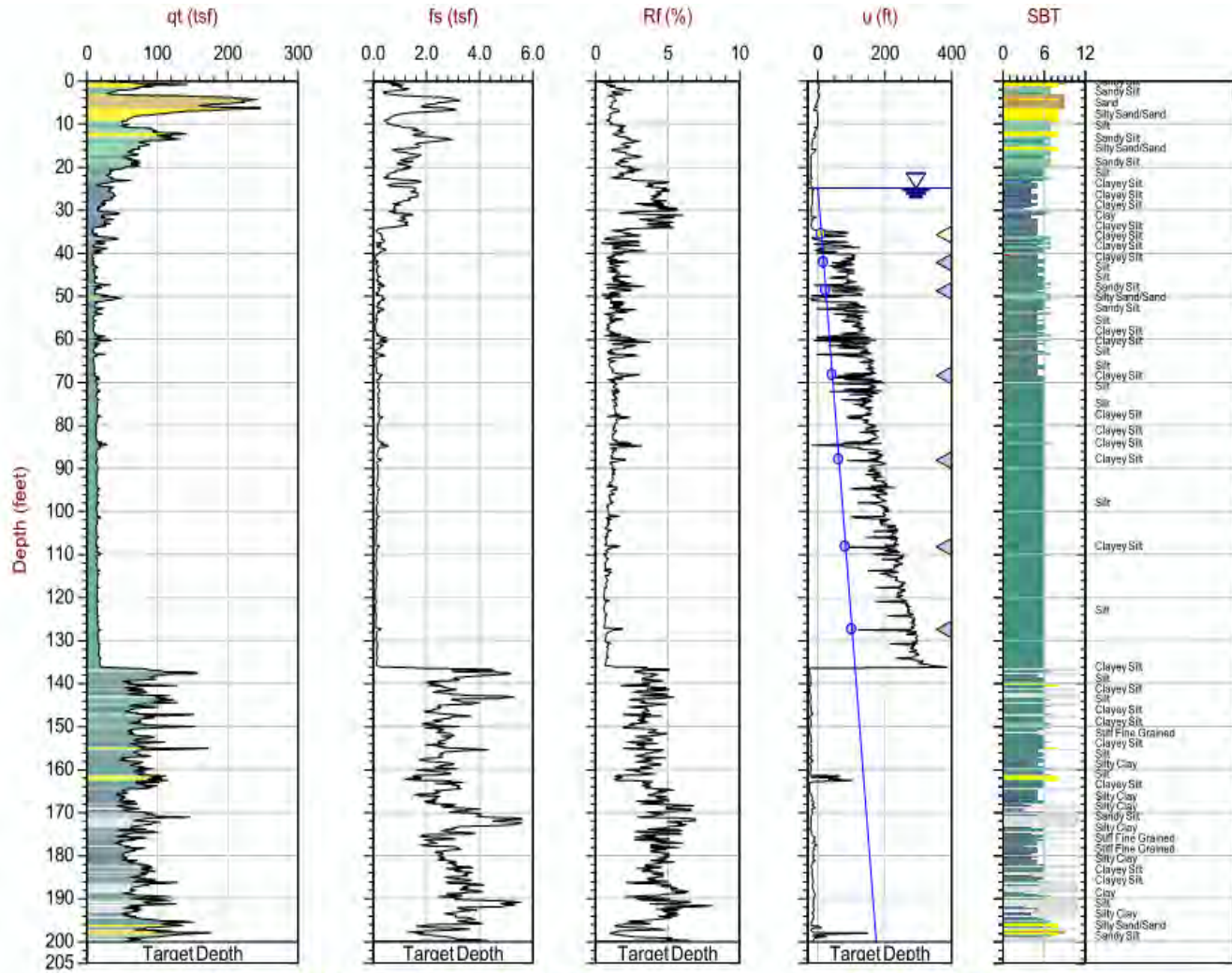
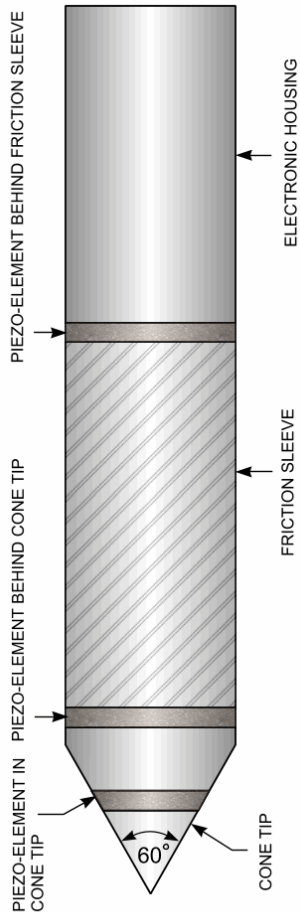


# CCR Field Testing Methods - PSCPT



# PS-CPT Field Testing Data

## CPT



Max Depth: 61.000 m / 200.13 ft File: 16-53085\_SPJ01.COR  
 Depth Inc: 0.050 m / 0.164 ft  
 Avg Int: Every Point

SBT: Robertson and Campanella, 1986  
 Coords: UTM Zone 17 N: 4171547m E: 427273m

— Hydrostatic Line ● Ueq ● Assumed Ueq ◁ PPD, Ueq achieved ◁ PPD, Ueq not achieved  
 The reported coordinates were acquired from consumer-grade GPS equipment and are only approximate locations. The coordinates should not be used for design purposes.



# PS-CPT Field Data Summary

<b>LAYER G</b>	Total Stress	Eff. Stress	Pore Press	(N <sub>1</sub> ) <sub>60</sub>	S <sub>U</sub>	Perm.	AvgQc	AvgFs	φ	OCR
	(tsf)	(tsf)	(tsf)	(blows/ft)	(tsf)	(cm/s)	(tsf)	(tsf)	(deg.)	
Sum (d)	2382.16	410.02	1972.14	7689.08	715.74	7.97E-02	25766.40	533.81	53245.13	61210.50
Num (N)	1531	1531	1531	1528	1531	1531	1531	1531	1510	1470
Median	1.45	0.24	1.22	3.14	0.23	1.82E-05	9.50	0.15	34.65	12.42
Mean (x)	1.56	0.27	1.29	5.03	0.47	5.20E-05	16.83	0.35	35.26	41.64
Maximum Value	3.08	0.72	2.36	69.67	9.63	5.02E-03	317.30	6.95	53.47	926.42
Minimum Value	0.17	0.00	0.17	0.00	0.00	5.00E-06	0.10	0.00	13.15	-5.31
Standard Deviation (e)	0.51	0.12	0.39	1.81	0.11	2.60E-05	2.80	0.11	0.99	3.97
<b>LAYER F</b>	Total Stress	Eff. Stress	Pore Press	(N <sub>1</sub> ) <sub>60</sub>	S <sub>U</sub>	Perm.	AvgQc	AvgFs	φ	OCR
	(tsf)	(tsf)	(tsf)	(blows/ft)	(tsf)	(cm/s)	(tsf)	(tsf)	(deg.)	
Sum (d)	951.98	171.05	780.93	3903.98	408.69	6.39E-03	14683.20	466.55	15959.10	15541.70
Num (N)	434	434	434	433	434	434	434	434	434	428
Median	2.15	0.40	1.77	6.44	0.59	9.24E-06	22.25	0.51	37.42	23.69
Mean (x)	2.19	0.39	1.80	9.02	0.94	1.47E-05	33.83	1.08	36.77	36.31
Maximum Value	3.45	0.77	2.68	117.05	7.60	6.76E-05	258.50	9.21	47.81	202.96
Minimum Value	1.35	0.11	1.18	0.70	0.00	4.06E-06	0.90	0.00	20.57	0.01
Standard Deviation (e)	0.38	0.09	0.29	2.54	0.21	3.60E-07	2.97	0.31	1.18	4.63
<b>LAYER E,D,C &amp; B</b>	Total Stress	Eff. Stress	Pore Press	(N <sub>1</sub> ) <sub>60</sub>	S <sub>U</sub>	Perm.	AvgQc	AvgFs	φ	OCR
	(tsf)	(tsf)	(tsf)	(blows/ft)	(tsf)	(cm/s)	(tsf)	(tsf)	(deg.)	
Sum (d)	10091.76	2348.51	7743.25	6049.58	1746.38	8.09E-03	24927.70	385.50	46325.56	6193.30
Num (N)	1871	1871	1871	1868	1871	1871	1871	1871	1871	1860
Median	4.82	1.10	3.73	2.79	0.58	3.47E-06	10.90	0.10	23.65	1.41
Mean (x)	5.39	1.26	4.14	3.24	0.93	4.33E-06	13.32	0.21	24.76	3.33
Maximum Value	10.39	2.74	7.65	28.54	15.70	1.45E-05	137.30	9.33	44.98	105.58
Minimum Value	2.82	0.45	2.37	1.09	0.00	1.14E-06	2.10	0.00	15.18	0.01
Standard Deviation (e)	0.74	0.21	0.53	0.89	0.48	1.66E-07	1.36	0.05	0.87	1.93

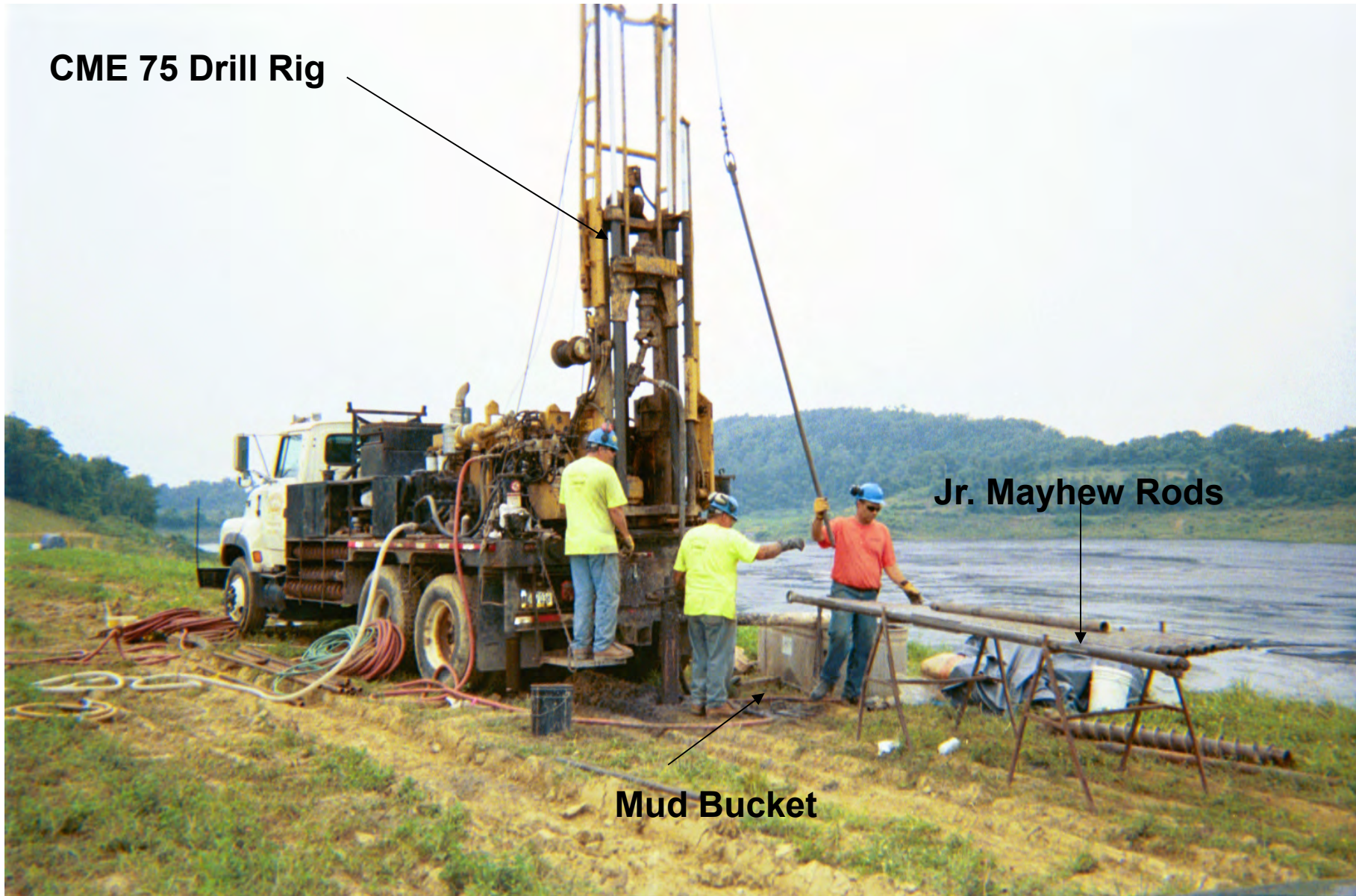
# CCR Field Testing Techniques

- Field Testing method:
  - 2. **Mud rotary drilling**
- Perform SPT and undisturbed sampling to collect samples and evaluate material interfaces due to:
  - Varying deposition environments, outlet locations;
  - Above/below water deposition;
  - Variations in fly ash, bottom ash, calcilox additions.
- Obtain high quality, undisturbed samples of ash for laboratory testing.

# CCR Field Testing Techniques

- Piston samples retrieved with hydraulically-actuated Gregory Undisturbed Sampler (GUS).
- Volume changes calculated from penetration and recovery measurements.
- Undisturbed samples are transported in specifically designed padded boxes to minimize disturbance.
- Changes in volume tracked prior to and following shipment to account for any disturbance.
- Samples are selected for laboratory testing based on the quality of the sample.

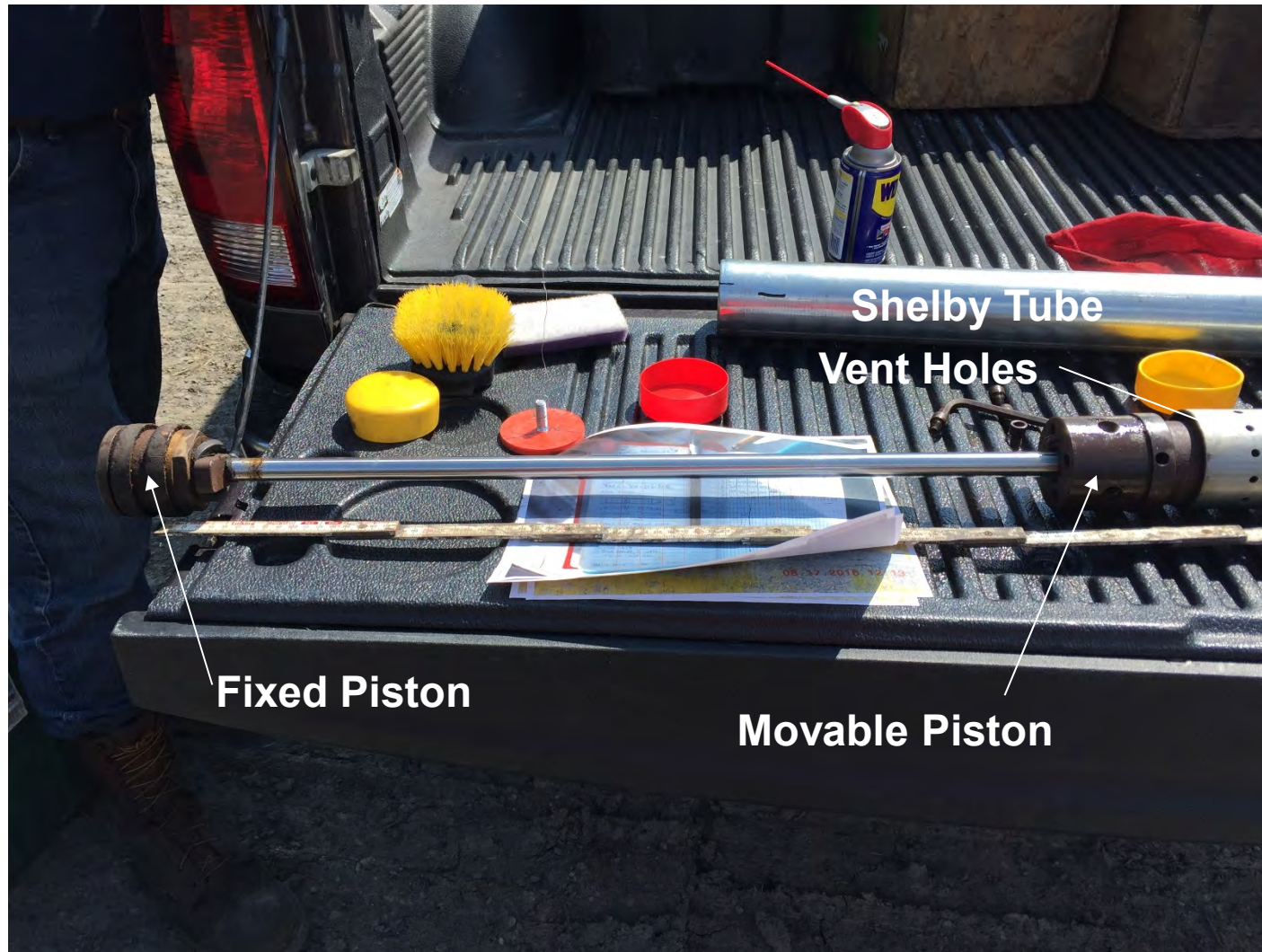
# CCR Field Testing – Fixed Piston Sampling



# CCR Field Testing – Fixed Piston Sampler



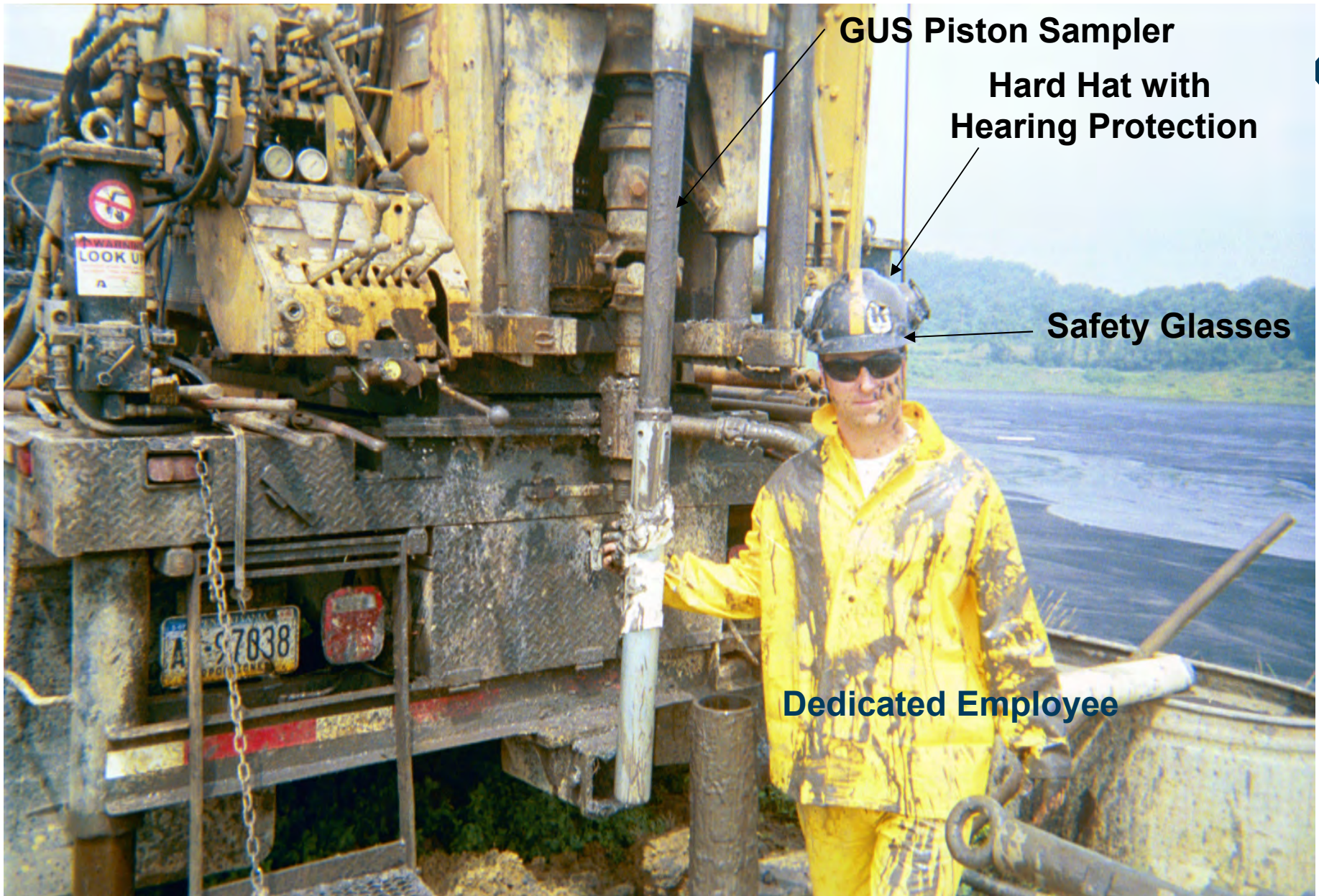
# CCR Field Testing – Fixed Piston Sampler



# CCR Field Testing – Fixed Piston Sampling



# CCR Field Testing – Fixed Piston Sampling

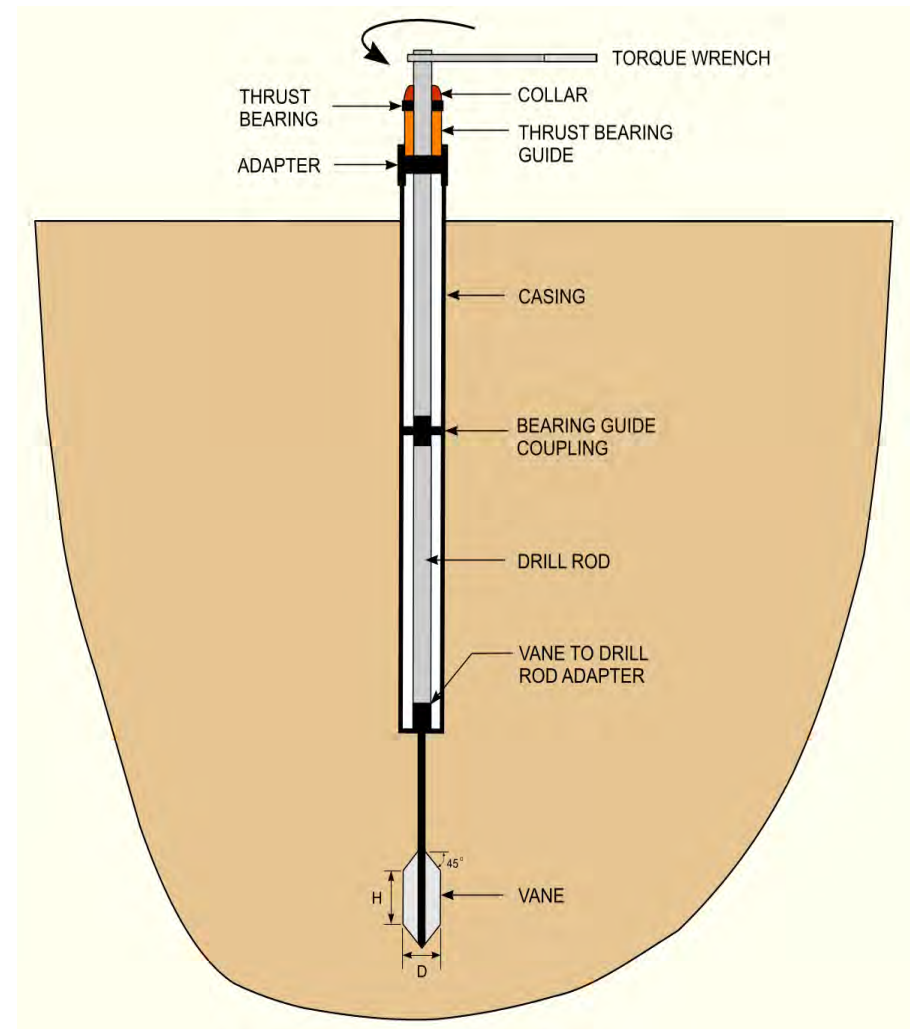


# CCR Field Testing – Sample Storage/Transportation



# Other Field Testing Methods –Vane-Shear Testing

- Measures undrained peak and steady-state strength.
- Used for Clay-like materials
- Not used for Sand-like materials.
- The material should remain undrained during the test.



# Typical Minimum Laboratory Testing Program

- Testing should include performing (at a minimum):
  - Natural water content;
  - Grain size analyses;
  - Atterberg limits;
  - Specific gravity;
  - Unit weight;
  - Consolidated-undrained (CU) triaxial testing;
  - 1-D consolidation testing; and,
  - Permeability testing.
- Testing performed on selected undisturbed ash samples.

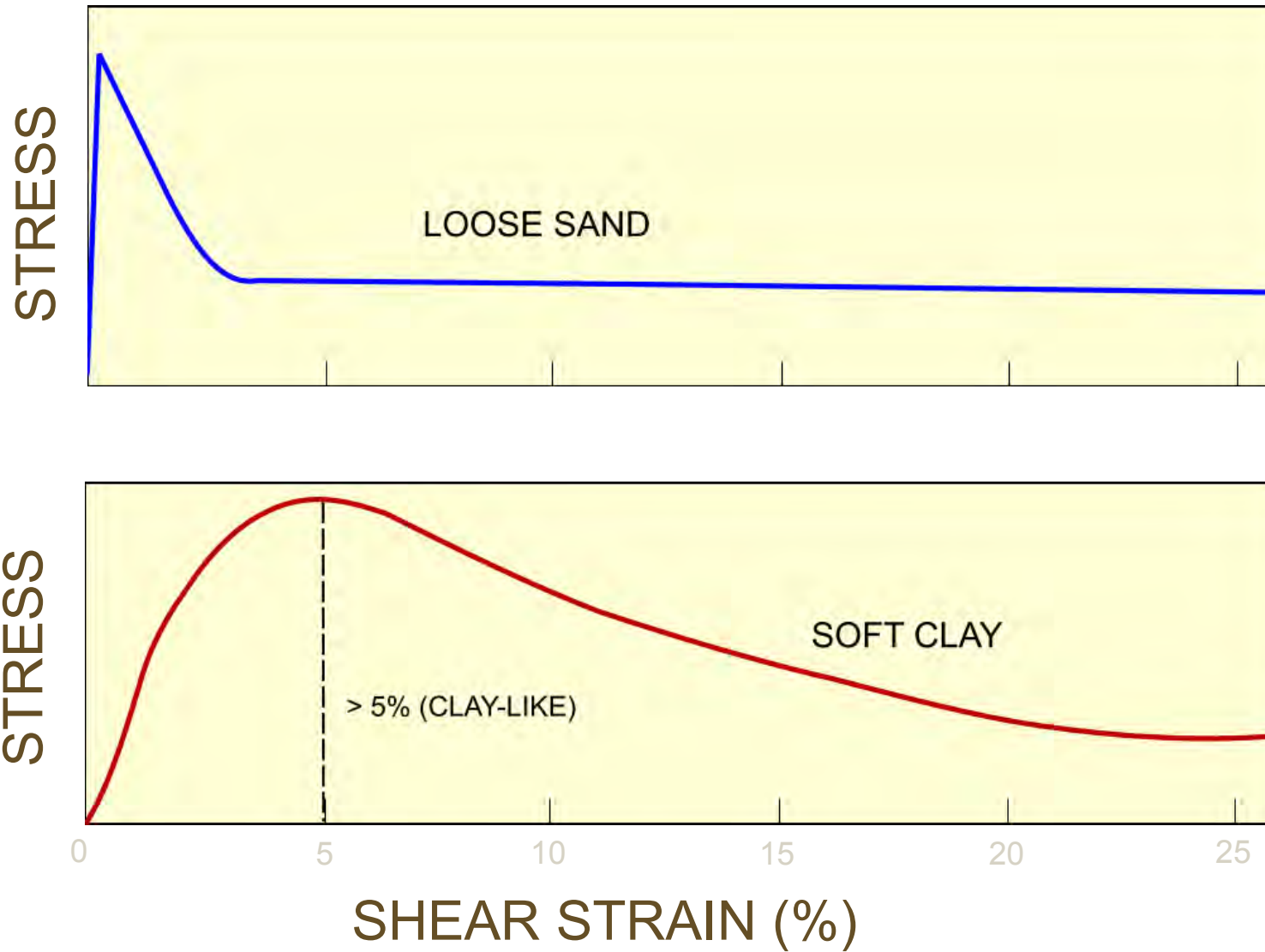
# Laboratory Testing Program

- Index testing provides for sand-like and/or clay-like material characterization.
- CU triaxial testing estimates peak and steady-state undrained shear strength, and peak axial strain for stability analyses.
- 1-D consolidation testing estimate parameters for settlement and loading rate analyses.
- CU and 1-D consolidation testing provide data to assess diagenesis (cementing) properties.
- Permeability testing estimates hydraulic conductivity and correlates CPT PPD-derived permeability.

# Characterizing CCR and Natural Soils

- Materials behave (in undrained shear) as:
  - Clay-Like
  - Sand-Like
- CPT and laboratory testing results used to characterize ash and soil as either sand-like or clay-like.
- Key differences between sand- and clay-like:
  - Strain at peak undrained shear strength
  - Abruptness of drop-off in shear resistance

# Sand-Like vs. Clay-Like



# Characterizing CCR and Natural Soils

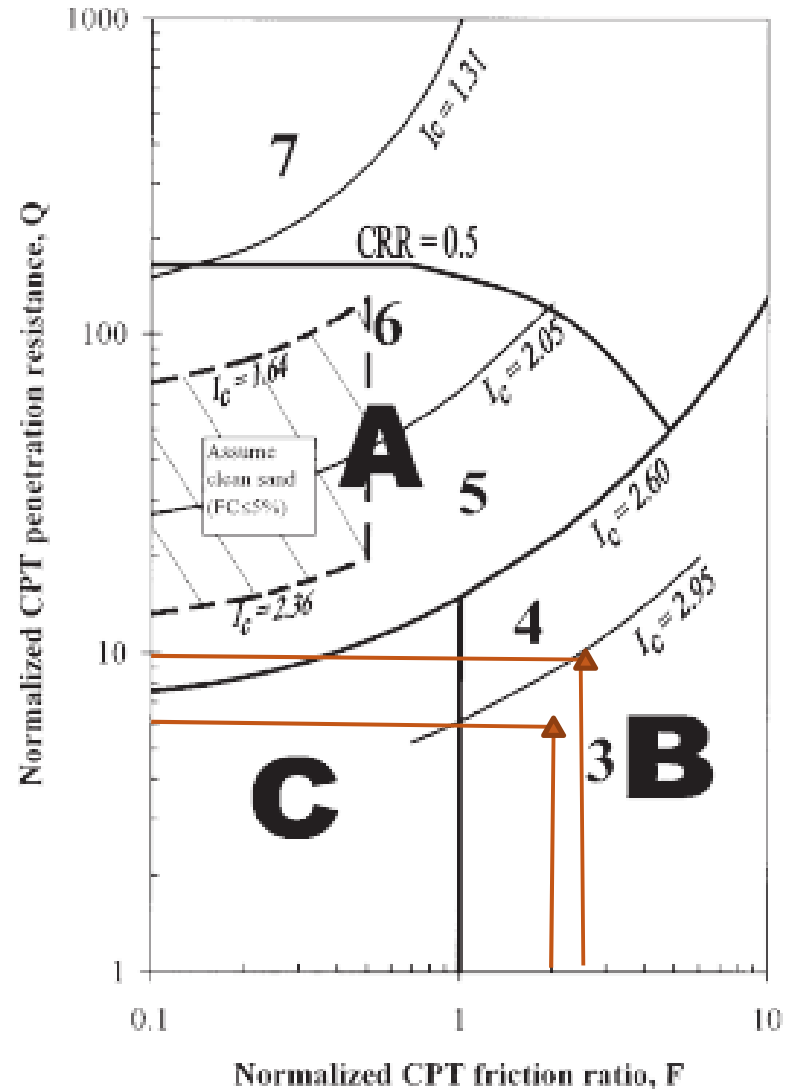
P. K. Robertson and C. E. (Fear) Wrode, (1998). "Evaluating Cyclic Liquefaction Potential Using the Cone Penetration Test," Canadian Journal of Geotechnical Engineering, Vol. 35, Pages 442-459.

Zone A: Liquefaction Possible – Depends on EQ M and duration.

Zone B: Liquefaction Unlikely – Check other criteria, i.e., cyclic stress/strain.

Zone C: Liquefaction Possible – Depends on plasticity and EQ.

Soils with  $I_c > 2.6$  and  $F > 1.0\%$  are likely non-liquefiable.

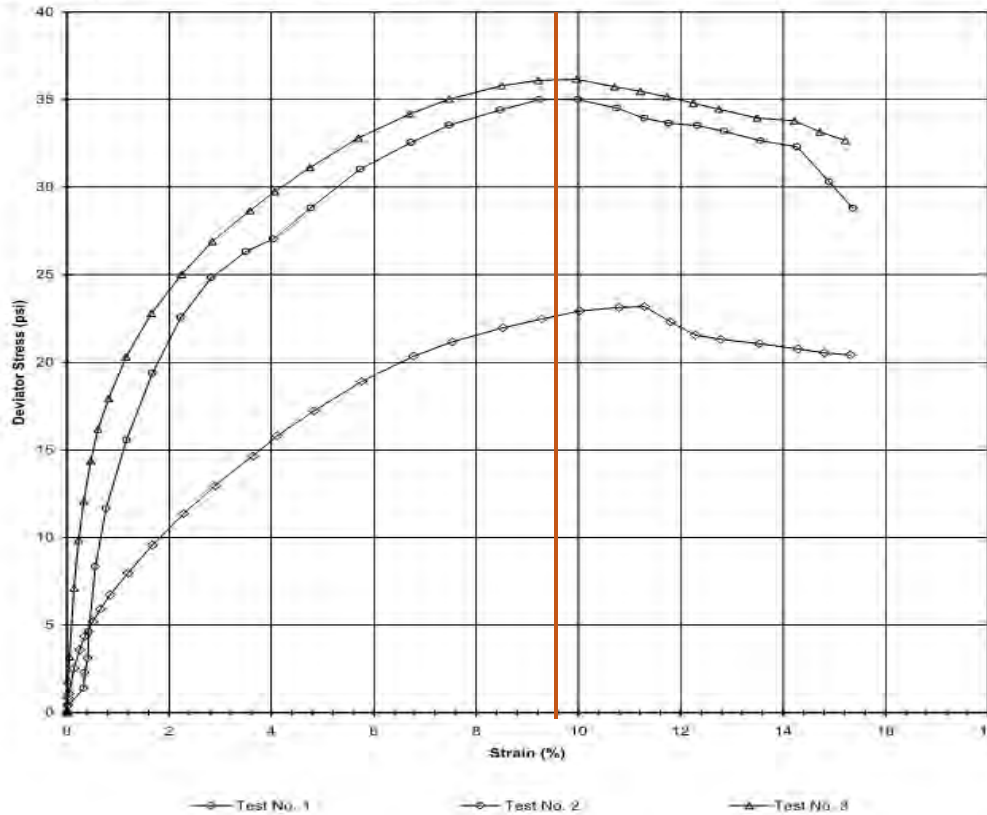


# Characterizing CCR and Natural Soils



## CONSOLIDATED UNDRAINED TRIAXIAL TEST WITH PORE PRESSURE READINGS ASTM D4767-11

Client:	GAI Consultants, Inc.	Boring No.:	D-5
Client Reference:		Depth (ft):	42.0-44.0
Project No.:	2015-253-003	Sample No.:	U-15
Lab ID:	2015-253-003-003		
Visual Description:	Black Ash (Undisturbed)		



Max Axial Strain = 9.5%

Max Shear Strain =  
1.5 \* Axial Strain = 14.3%

Tested By: JAB      Date: 7/14/15      Approved By: DB      Date: 7/21/15

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# Engineering Properties Summary

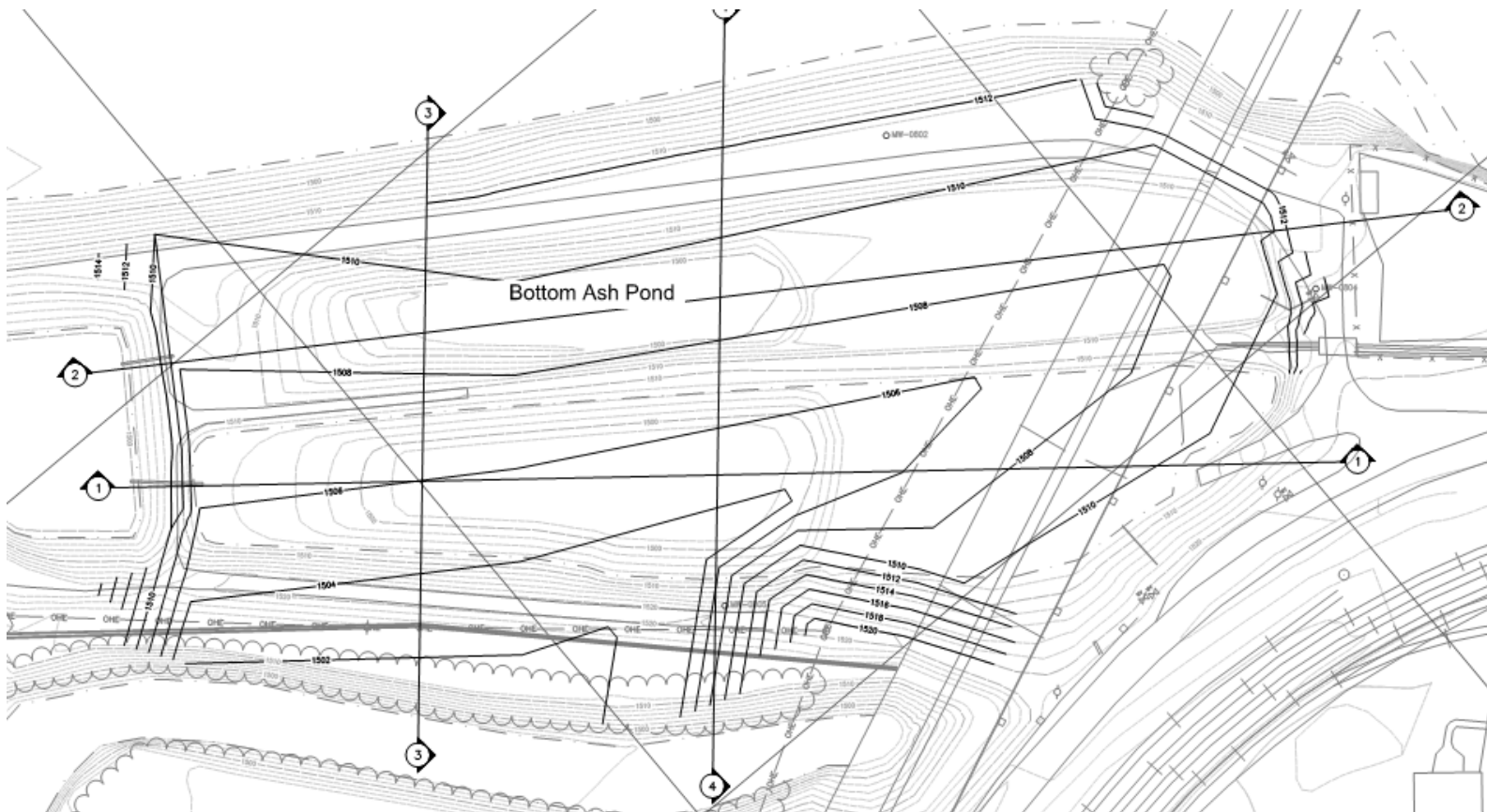
Boring I.D.	Sample I.D.	Depth (ft)	SOIL ENGINEERING PROPERTIES										
			In-situ Parameters			Consolidated Un drained Triaxial				One-Dimensional Consolidation			
			$w_{nat}$ (%)	Dry Unit Weight, $\gamma_d$ (pcf)	Moist Unit Weight, $\gamma_m$ (pcf)	$\phi'$ (deg)	$c'$ (psi)	$\phi$ (deg)	$c$ (psi)	$e_0$	$C_c$	$C_r$	OCR
ASH D-1	ST-7	12.0 - 14.0	98.3	38.1	75.5	36.6	0.5	17.9	3.7	1.646	0.474	0.027	5.781
ASH D-2	ST-14	27.4 - 27.9	82.1	49.7	90.4	38.6	0.1	22.4	2.4	1.902	0.334	0.055	3.042
ASH D-4	U-8	14.0 - 16.0	36.5	62.6	85.5	43.3	0.0	26.5	4.1	1.472	0.419	0.013	6.074
ASH D-5	U-5	22.0 - 24.0	103.3	39.5	80.2	34.9	2.2	16.3	8.8	1.752	0.384	0.048	4.155
ASH D-5	U-15	42.0 - 44.0	75.7	48.1	84.4	35.7	1.0	16.5	4.4	1.386	0.305	0.072	2.326
ASH D-6	U-3	13.0 - 15.0	82.4	42.8	78.1	33.8	2.5	15.2	11.2	0.926	0.103	0.007	6.825

# Deep-Seated Stability - CCR Rule Requirements

- Periodic Safety Factor Assessments - 257.73(e)(1)  
(i, ii, and iii)
  - “The owner or operator must conduct initial/periodic safety factor assessments”
- Target Safety Factors
  - Static, long-term, maximum storage pool loading condition: 1.50
  - Static, maximum surcharge pool loading condition: 1.40
  - Seismic: 1.00
- Therefore, proposed closure must be analyzed for:
  - Potential failure through
    - Foundation soil;
    - Impounded CCR; and,
    - Embankment material.

# Deep-Seated Stability – Steps to Perform Analysis

## 1. Develop cross-sections for analysis



# Deep-Seated Stability – Steps to Perform Analysis

## 2. Review results of

- Subsurface investigation program (drilling and in-situ methods)
- Available site literature (USGS maps, mine maps, soils maps)
- Soil/CCR laboratory data (index and strength tests)

# Deep-Seated Stability – Steps to Perform Analysis

## 3. Prepare Stability Model

- Review proposed grading plan
- Determine site seismic conditions
- Assign strength parameters to soils and CCR

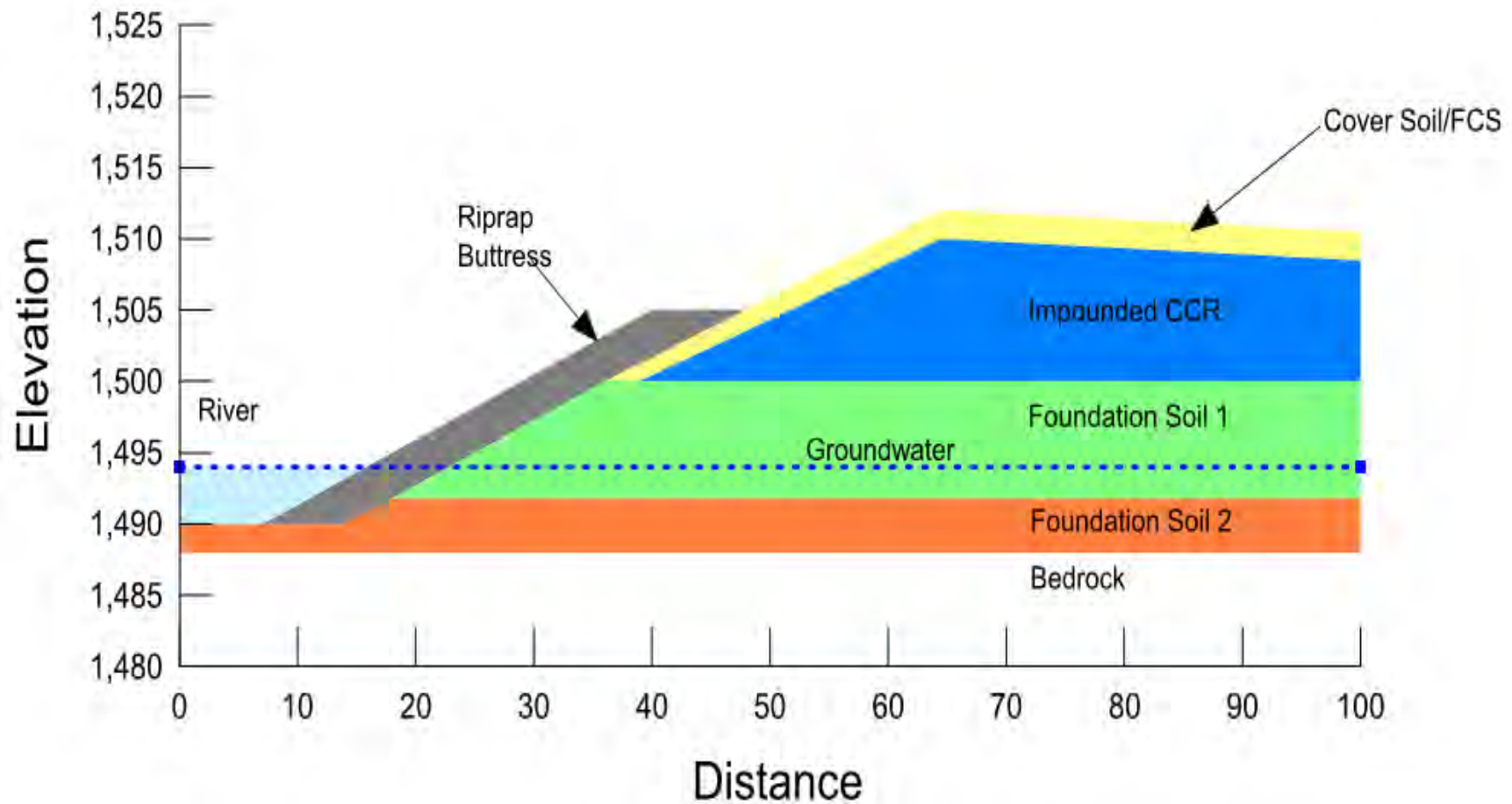
Material	Total Unit Weight, $\gamma$ (PCF)	Drained Friction Angle, $\phi$
Cover Soil	120	28 <sup>0</sup>
Impounded CCR	105	30 <sup>0</sup>
Foundation Soil 1	110	28 <sup>0</sup>
Foundation Soil 2	120	32 <sup>0</sup>

# Deep-Seated Stability – Steps to Perform Analysis

## 3. Prepare Stability Model (Cont.)

- Determine layer thicknesses:
  - Foundation Soil;
  - Embankment Materials;
  - Impounded CCR; and,
  - Final Cover System.
- Determine depth to bedrock
- Determine piezometric surface location

# Deep-Seated Stability – Steps to Perform Analysis



# Deep-Seated Stability – Steps to Perform Analysis

## 4. Analyze Cross-Sections Most Susceptible to Instability

- Foundation soil layer(s)
- Areas with greatest CCR fill depth

## 5. Stability Analysis Methods

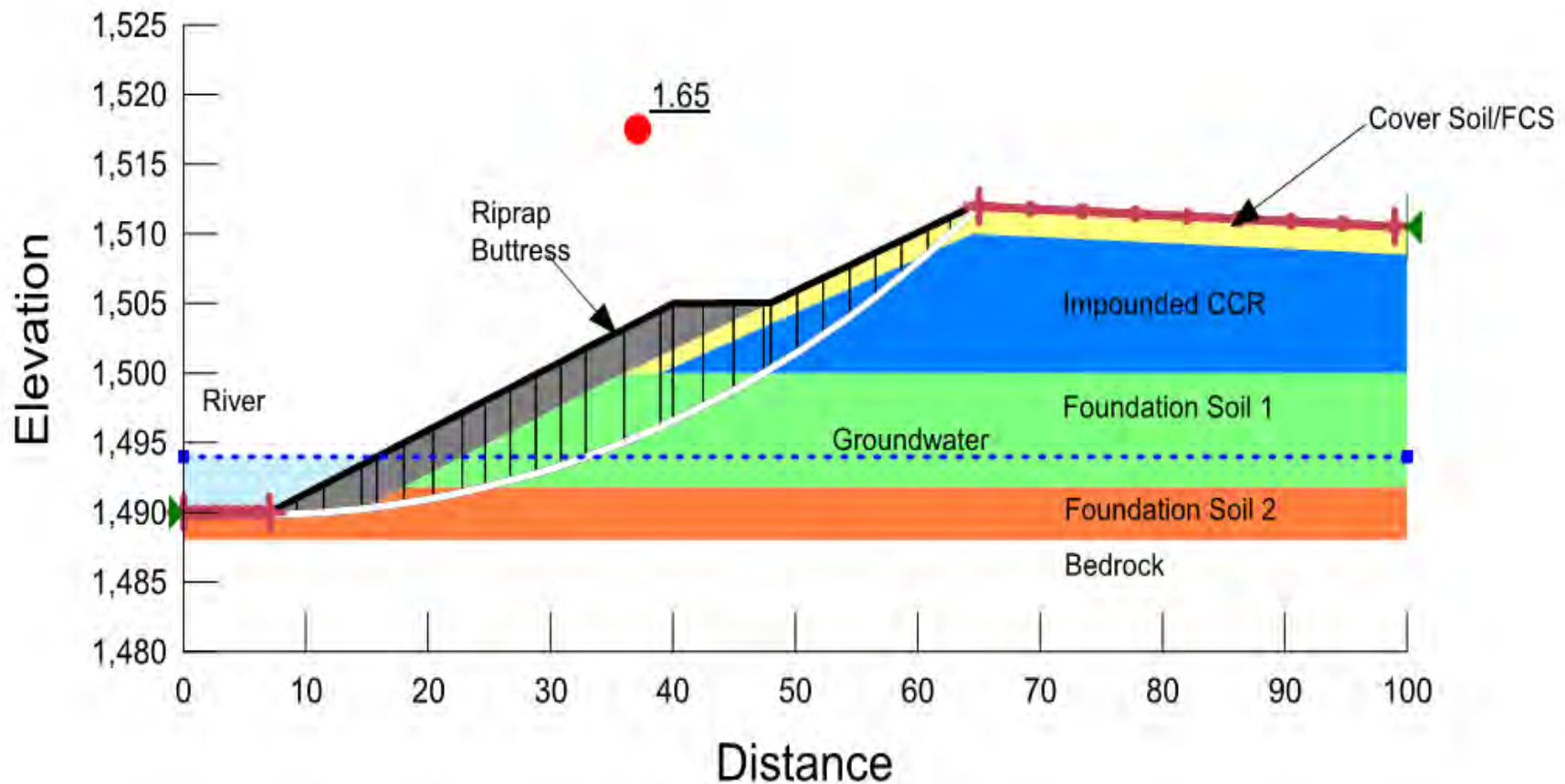
- Two-dimensional, limit equilibrium OR
- Finite element

## 6. Analysis conditions

- Static, long-term, dry and saturated
- Seismic

# Deep-Seated Stability – Steps to Perform Analysis

## 7. Evaluate Potential Rotational Slip Surfaces



# Settlement - CCR Rule Requirements

- Settlement Criteria for Conducting Closure of CCR Impoundment - 257.102(d)(3)(i)(D)
  - “The disruption of the integrity of the final cover system (FCS) must be minimized through a design that accommodates settling and subsidence”.
- Therefore, proposed closure must be analyzed for:
  - Potential settlement of
    - Foundation soil;
    - Impounded CCR; and,
    - Embankment material.

# Settlement - Steps to Perform Analysis

## 1. Prepare Settlement Model

- Review proposed grading plan
- Assign strength parameters to soils and CCR
- Determine layer thicknesses: Foundation Soil, Embankment Materials, Impounded CCR, FCS
- Determine depth to bedrock
- Determine piezometric surface location

# Settlement - Steps to Perform Analysis

## 2. Analyze Areas with Largest Settlement Potential

- Foundation/embankment soil layer(s) most susceptible to settlement/consolidation
- Areas with greatest CCR fill depths

## 3. Settlement Analysis Methods

- Elastic Settlement
  - Used to analyze cohesionless material
- Consolidation Settlement ( $C_c/C_r$ )
  - Used to analyze cohesive material

# Settlement - Steps to Perform Analysis

## 4. Determine Post-Settlement Impact on:

- Proposed grading plan
- Drainage pipes and channels
- Strains on geosynthetics

# Settlement - Steps to Perform Analysis

## Post-Settlement Grading



# Final Cover System - CCR Rule Requirements

- Veneer Stability Criteria for Conducting Closure of CCR Impoundment - 257.102(d)(1)(iii)
  - “Include measures that provide for major slope stability to prevent sloughing or movement of the FCS during closure and post-closure”
- Therefore, proposed closure must be analyzed for:
  - Potential failure along
    - Cover soil/CCR interface; OR
    - Cover soil/Geonet interface; and,
    - Geonet/Geomembrane interface; and,
    - Geomembrane/CCR interface.

# Final Cover System - CCR Rule Requirements

- FCS Criteria for Conducting Closure of CCR Impoundment - 257.102(d)(3)(i)(D)(A, B, C)
- Permeability of FCS must be less than or equal to permeability of
  - Bottom liner system OR
  - Natural subsoils OR
  - Permeability no greater  $1 \times 10^{-5}$  cm/sec
- FCS components:
  - 18-inch thick infiltration layer, AND
  - 6-inch thick erosion layer OR
  - Alternative FCS (i.e. geomembrane)

# Final Cover System - Steps to Perform Analysis

1. Develop typical cross-sections for analysis
2. Develop laboratory testing program
  - Natural water content;
  - Grain size analyses;
  - Atterberg limits;
  - Standard Proctor;
  - Relative Density; and,
  - Interface shear strength testing.

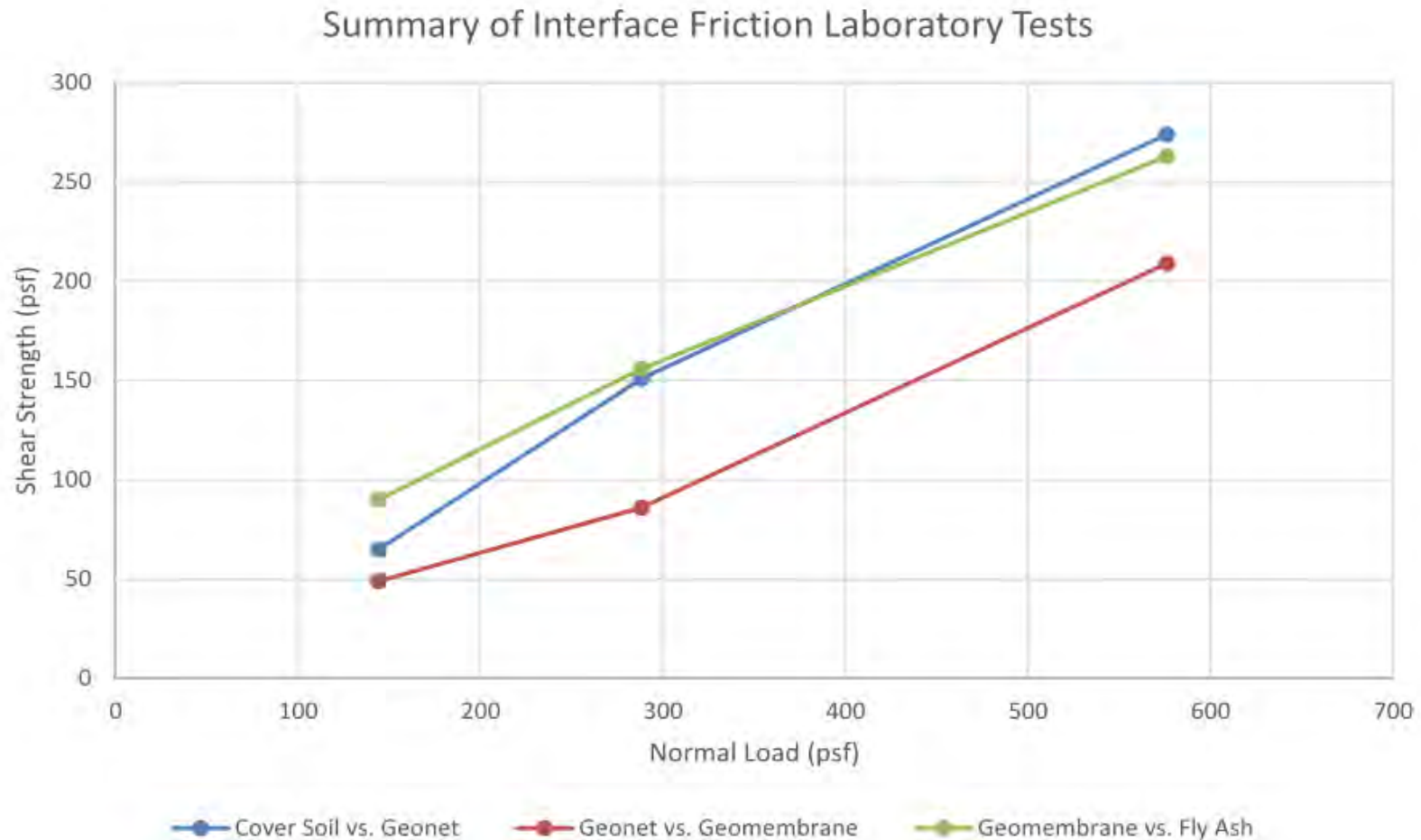
# Final Cover System - Steps to Perform Analysis

## 3. Typical Interface Shear Strength Testing Program

Testing Set-Up		
ASTM D5321	Conditioning	Set up each test to match field placement orientation. Run all tests under wet conditions.
	Procedure A	Testing interface: Cover Soil against Geonet Substrate: cover soil at 85% Standard Proctor MDD $\pm$ 3% OMC (OMC preferred) Super-stratum: steel rasp platen Displacement Rate: 0.04 ipm (maximum) Total Displacement: 2.50 in (minimum)
	Procedure B	Testing interface: Geonet against Geomembrane Substrate: steel rasp platen Super-stratum: steel rasp platen Displacement Rate: 0.20 ipm (maximum) Total Displacement: 2.50 in (minimum)
	Procedure C	Testing interface: Geomembrane against Fly Ash Substrate: fly ash at 94% Standard Proctor MDD $\pm$ 3% OMC (OMC preferred) Super-stratum: steel rasp platen Displacement Rate: 0.04 ipm (maximum) Total Displacement: 2.50 in (minimum)

# Final Cover System - Steps to Perform Analysis

## 4. Review interface shear strength testing results

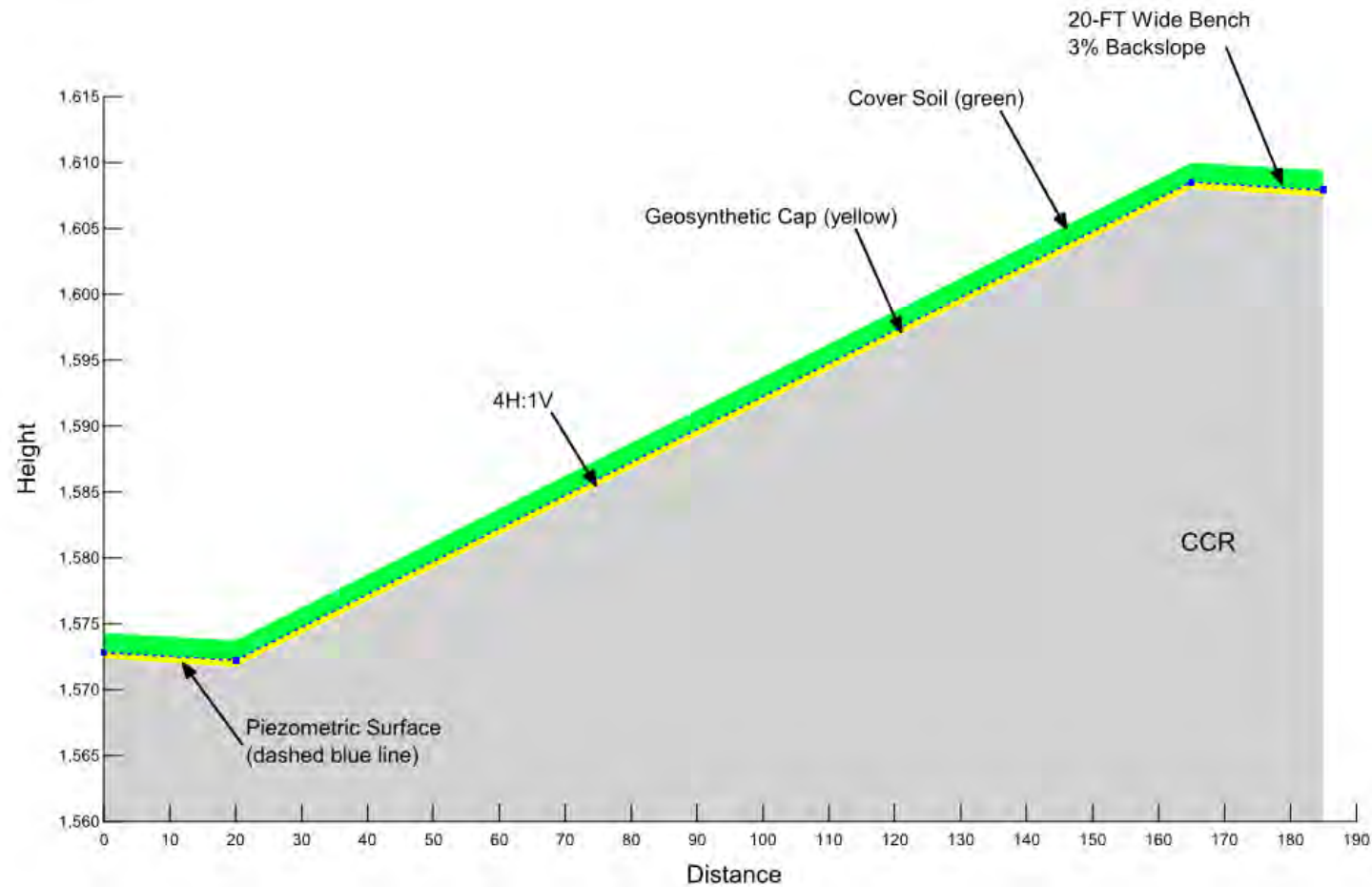


# Final Cover System - Steps to Perform Analysis

## 5. Prepare Veneer Stability Model

- Review proposed grading plan
- Determine site seismic conditions
- Assign strength parameters to soils, CCR, and geosynthetic layer
- Determine piezometric surface location from HELP model or place within drainage layer (geonet)

# Final Cover System - Steps to Perform Analysis



# Final Cover System - Steps to Perform Analysis

## 6. Analyze critical sections

- Steepest; and,
- Longest slopes

## 7. Analysis methods:

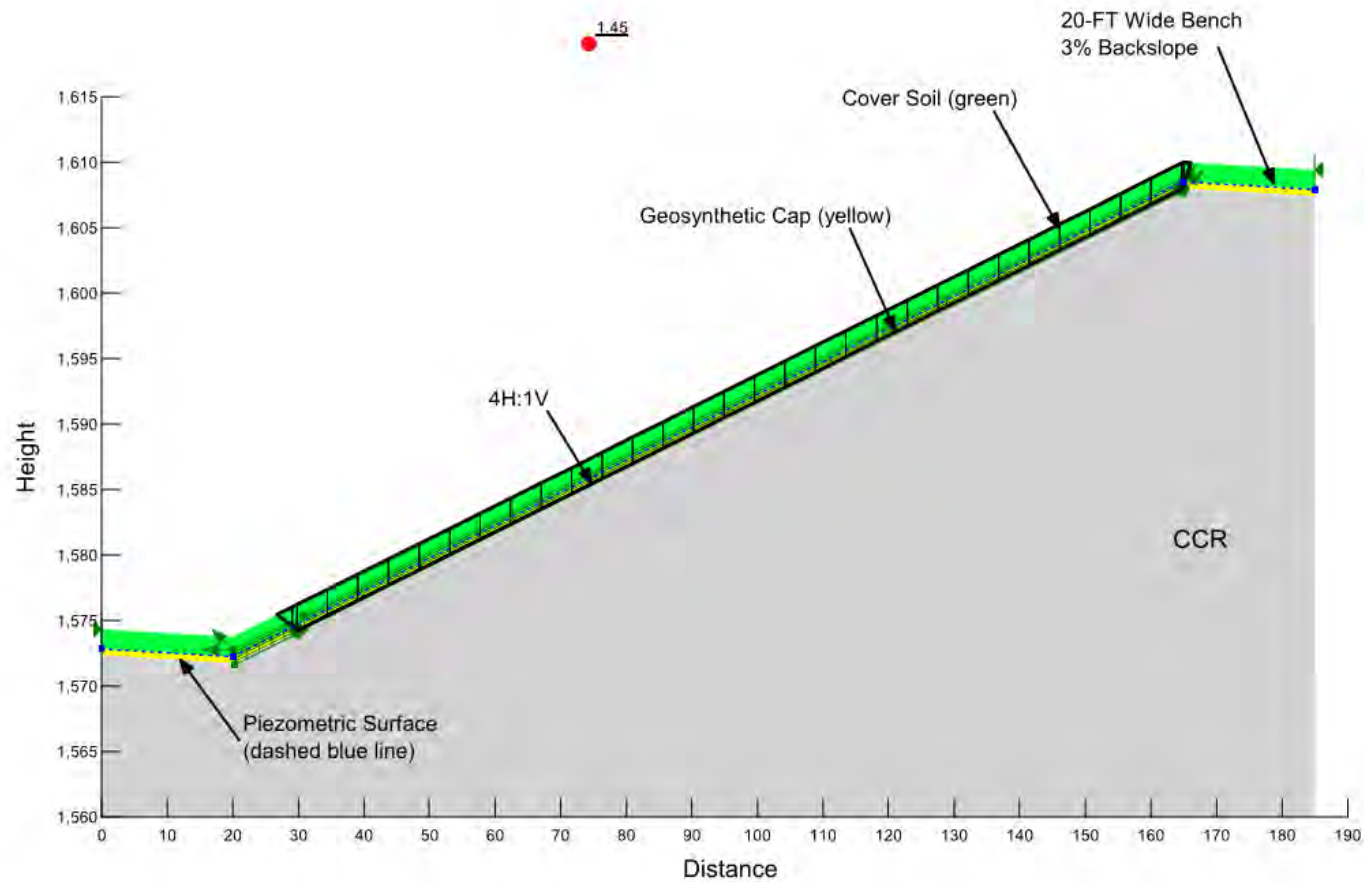
- Two-dimensional, limit equilibrium OR
- Infinite slope

## 8. Analysis conditions:

- Static, long-term, both dry and saturated
- Seismic

# Final Cover System - Steps to Perform Analysis

## 9. Evaluate shallow block slip surfaces within FCS



# What is Liquefaction?

1. Loss of soil strength during or following an earthquake often leading to a flow-slide failure.
2. Significant increase in pore pressure caused by earthquake shaking resulting in sand boils at the surface of level ground.
3. Lateral spreading, the lateral displacement of large blocks of soil from liquefaction in a subsurface layer.
4. Ground oscillation, decoupling of overlying soil blocks that jostle back and forth atop a liquefied layer.

# What is Liquefaction? – Flow Slide



# What is Liquefaction? – Sand Boil



# What is Liquefaction? – Lateral Spreading



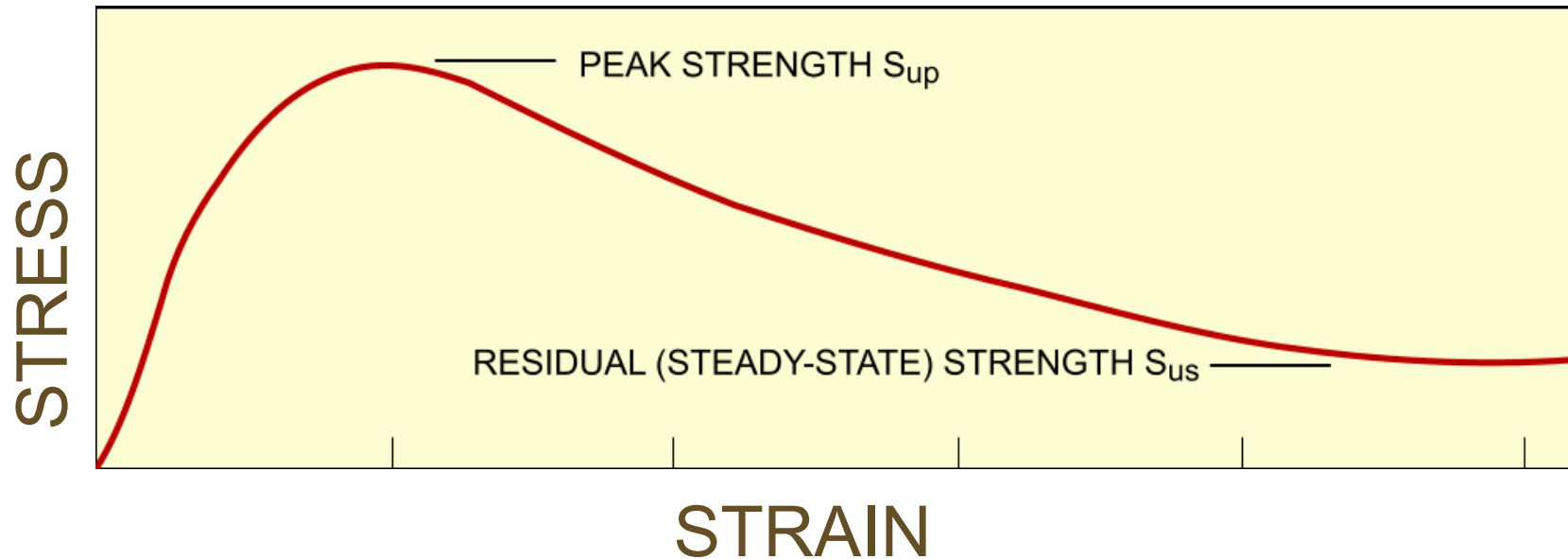
# What is Liquefaction? – Ground Oscillation



**Photo from Wilbur Smith collection  
Courtesy of Robert B. Smith**

# What is Liquefaction? – Strength Loss

## Undrained Stress-Strain Curve for Material Subject to Strength Loss



# For Liquefaction to Occur, 3 Conditions Must Develop

1. Earthquake shaking must be strong enough to trigger undrained strength loss in one or more zones.
2. Strength loss must be significant enough that post-earthquake strengths are less than static driving stresses.
3. Amount of material that experiences strength loss must be sufficient to generate instability.

# Basic Elements of CCR Liquefaction/Seismic Analysis

1. Characterize ash and soil materials within the embankment, impoundment, and foundation.
2. Evaluate susceptibility of materials to strength loss.
3. Evaluate if design earthquake will trigger strength loss.
4. Perform pseudo-static stability with  $FS \geq 1.0$  acceptance criteria.

# Liquefaction/Seismic Stability of CCR Impoundments

Per CCR Rule, seismic design of CCR impoundments generally involves two separate evaluations:

1. Section 257.73(e)(1)(iii) requires a Post-Earthquake Slope Stability with a minimum FS of 1.0.
  - Pseudo-static (seismic) stability analysis include the 2% in 50 year, 1.0-second spectral acceleration as horizontal seismic input.
  - Strength properties based on results of liquefaction analysis.

# Liquefaction/Seismic Stability of CCR Impoundments

2. Section 257.73(e)(1)(iv) requires a liquefaction analysis that determines the post-earthquake strength properties based on FS above or below 1.2.

- Evaluates potential for triggering loss of strength.
- If  $FS \geq 1.2$ , peak undrained strength properties used in seismic stability analyses; or,
- If  $FS < 1.2$ , use steady-state strength properties.

# Empirical Liquefaction Analysis Methodologies

## Field Testing Approach for Sand-Like Materials

- Youd et al. (2001) represents consensus of many experts for the method.

## Laboratory Testing Approach for Clay-Like Materials

- Boulanger and Idriss (2007) evaluates cyclic softening of silts and clays.

# CCR Liquefaction Analyses

## Generalized Empirical Approach

Factor of safety against liquefaction:

$$FS = (CRR_{7.5}/CSR) \cdot MSF \cdot K_{\sigma} \cdot K_{\alpha}$$

CRR = Cyclic Resistance Ratio (from SPT/CPT, lab data)

CSR = Cyclic Stress Ratio (induced by EQ,  $a_{max}$  surface acceleration)

MSF = Correction for EQ magnitude

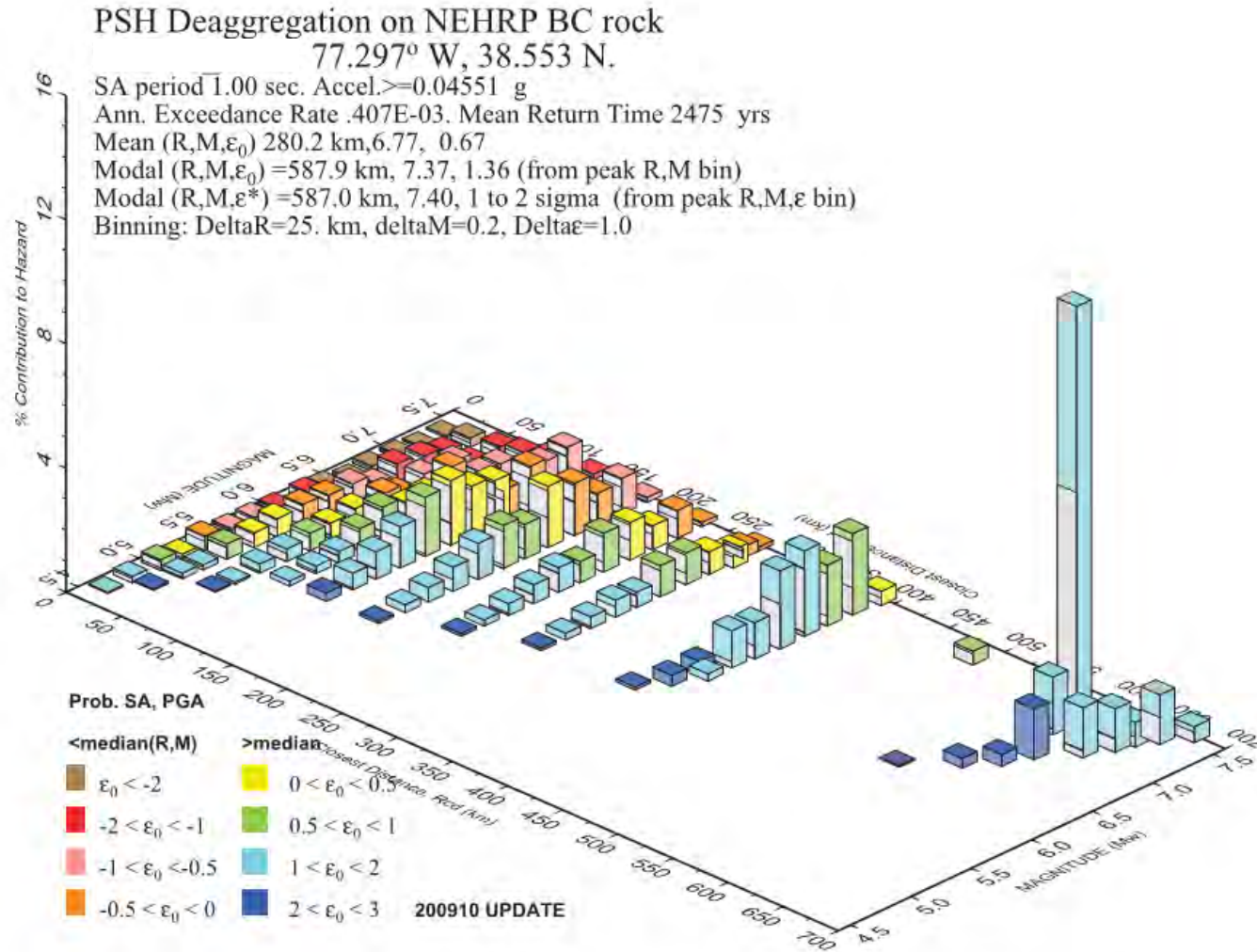
$K_{\sigma}$  = Correction for overburden

$K_{\alpha}$  = Correction for shear stress

# CCR Liquefaction SHAKE Analyses Profile

SUMMARY OF SHAKE INPUT PARAMETERS				
NODE 119 GENERALIZED PROFILE				
SURFACE EL. = 108.68 FT; GWT DEPTH = 21.0 FEET; 5% DAMPING				
MATERIAL TYPE	LAYER THICKNESS (FT)	LAYER NO.	DEPTH BELOW GROUND SURFACE (FT)	LAYER AVERAGE SHEAR MODULUS, G (KSF)
COVER SOIL (Total Unit Wt.=110 pcf)	2	1	2	650
PROPOSED ASH FILL (Total Unit Wt.=83 pcf)	3	2	5	500
	4	3	9	500
	4	4	13	600
EXISTING ASH (Total Unit Wt.=82 pcf)	4	5	17	237
	5	6	22	327
	5	7	27	368
	5	8	32	540
RESIDUAL SOIL (Total Unit Wt.=118 pcf)	5	9	37	1191
	5	10	42	1751
	5	11	47	2023
ROCK (SANDSTONE) (Total Unit Wt.=150 pcf)		12		Vs = 4000 fps

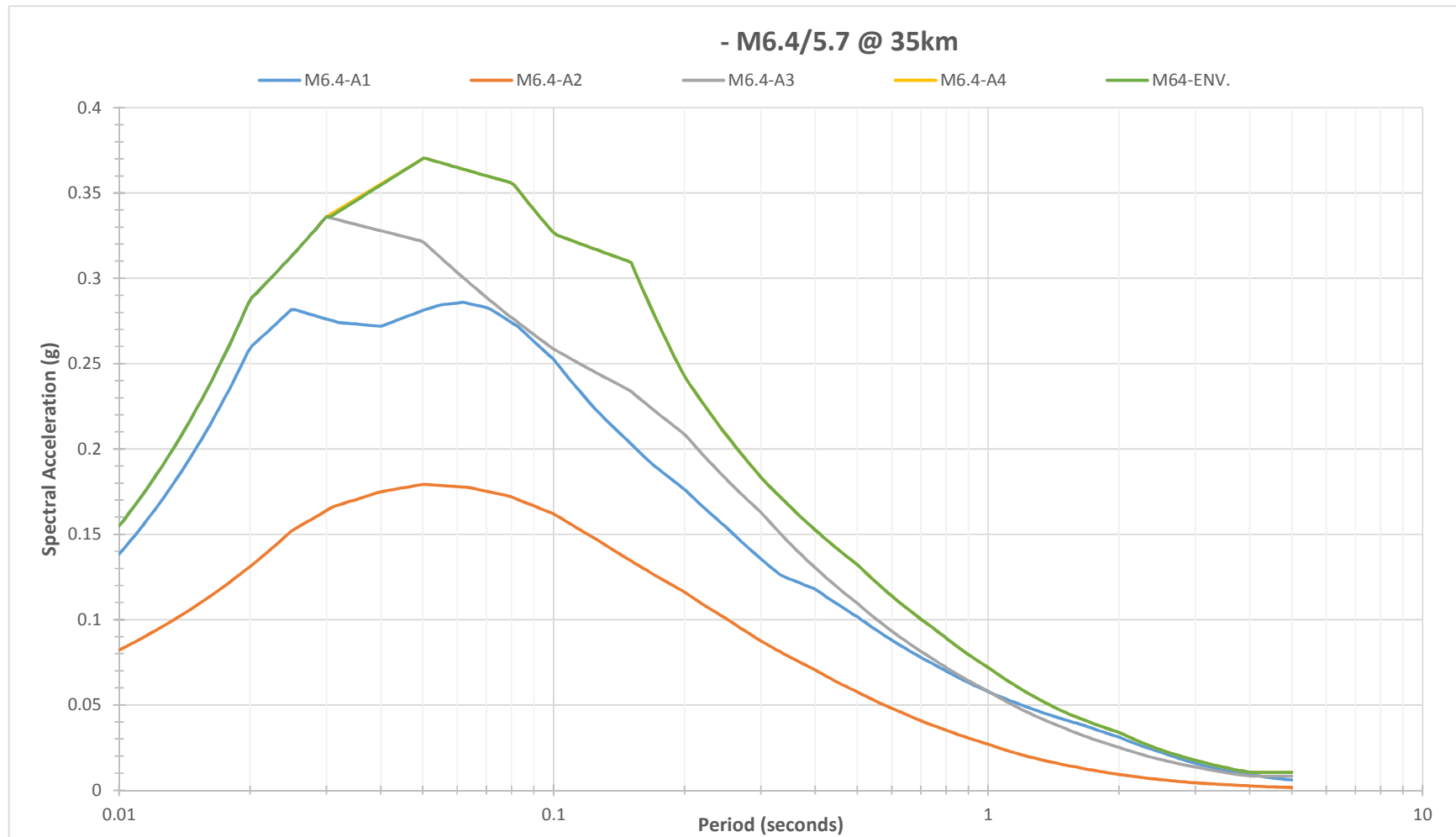
# 2009/10 USGS Deaggregation Map – 1.0 sec.



GMT 2016 Dec 14 15:17:35 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

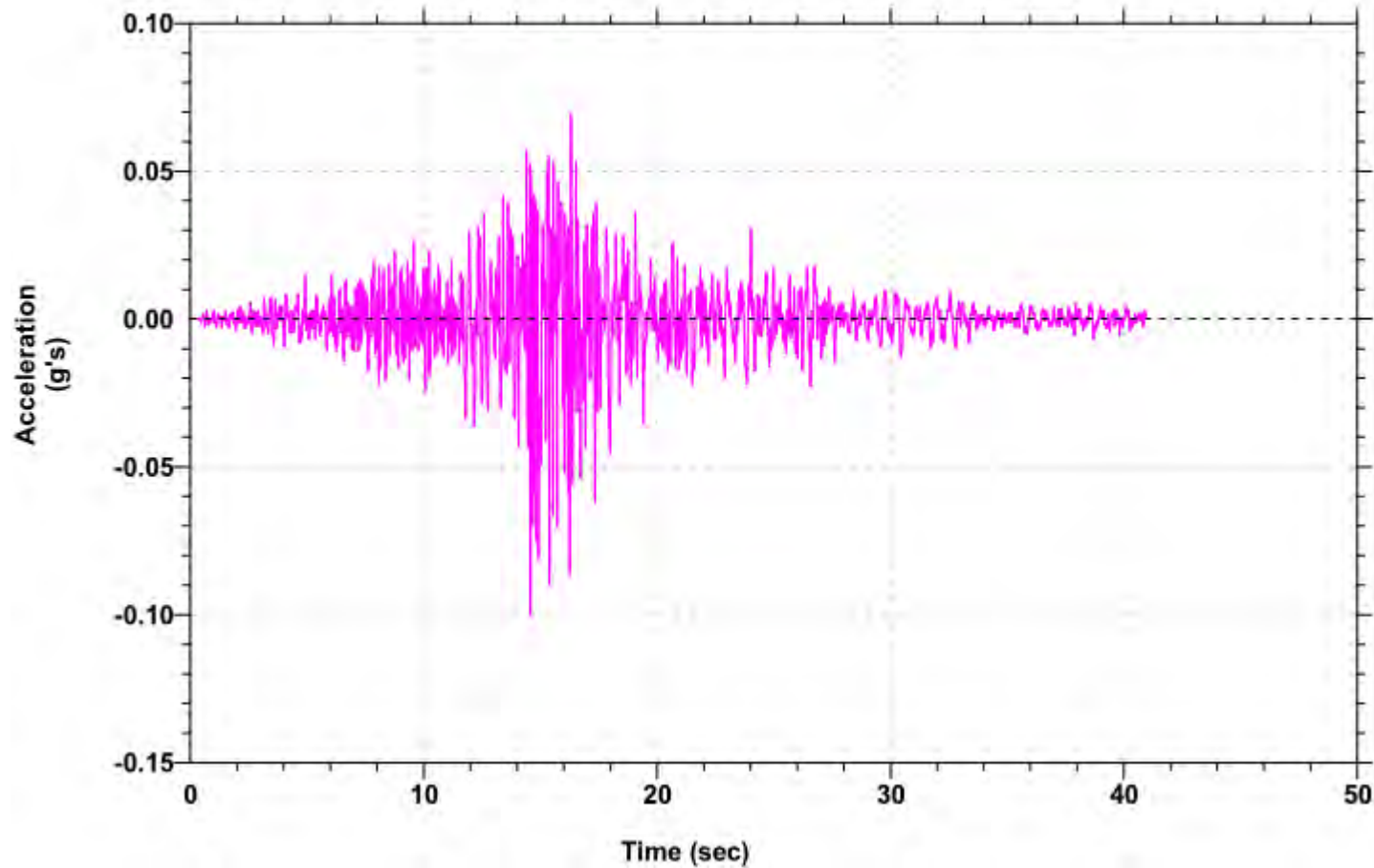
# CCR Liquefaction Analyses – SHAKE Input Spectra

## Envelope Response Spectra



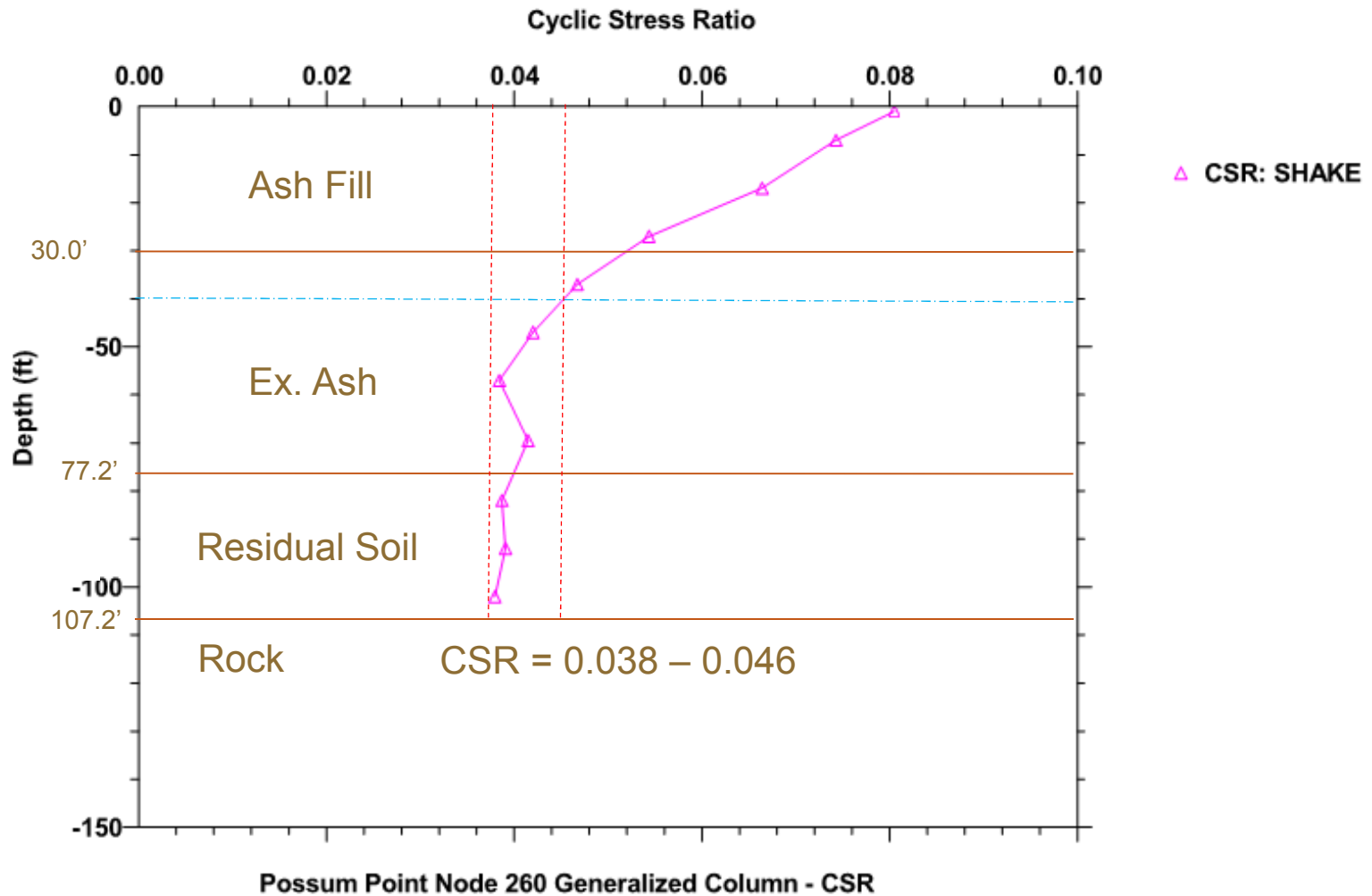
# CCR Liquefaction Analyses – SHAKE Input Spectra

## Spectrally Matched Time History

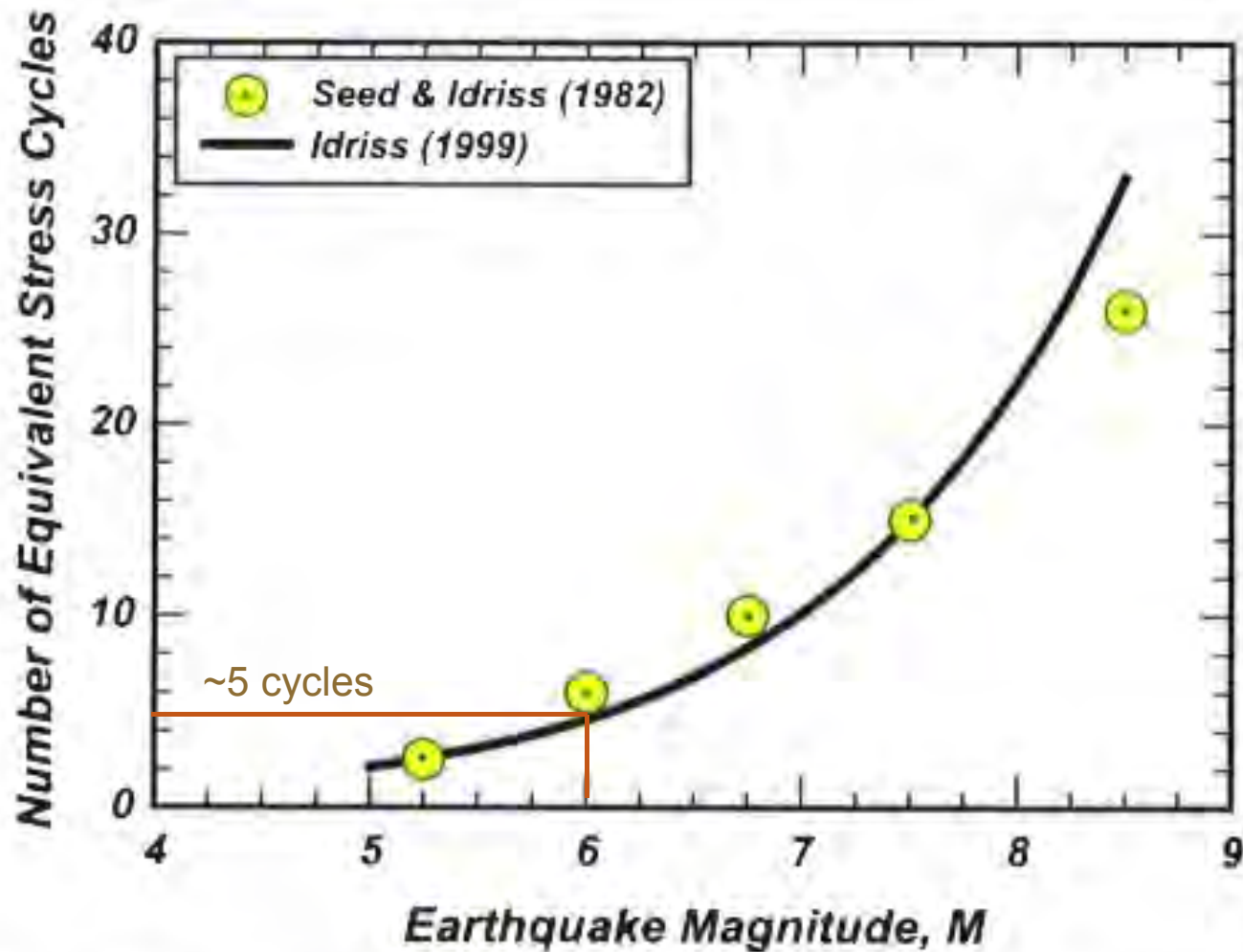


# CCR Liquefaction Analyses – SHAKE Results

## Cyclic Stress Ratio

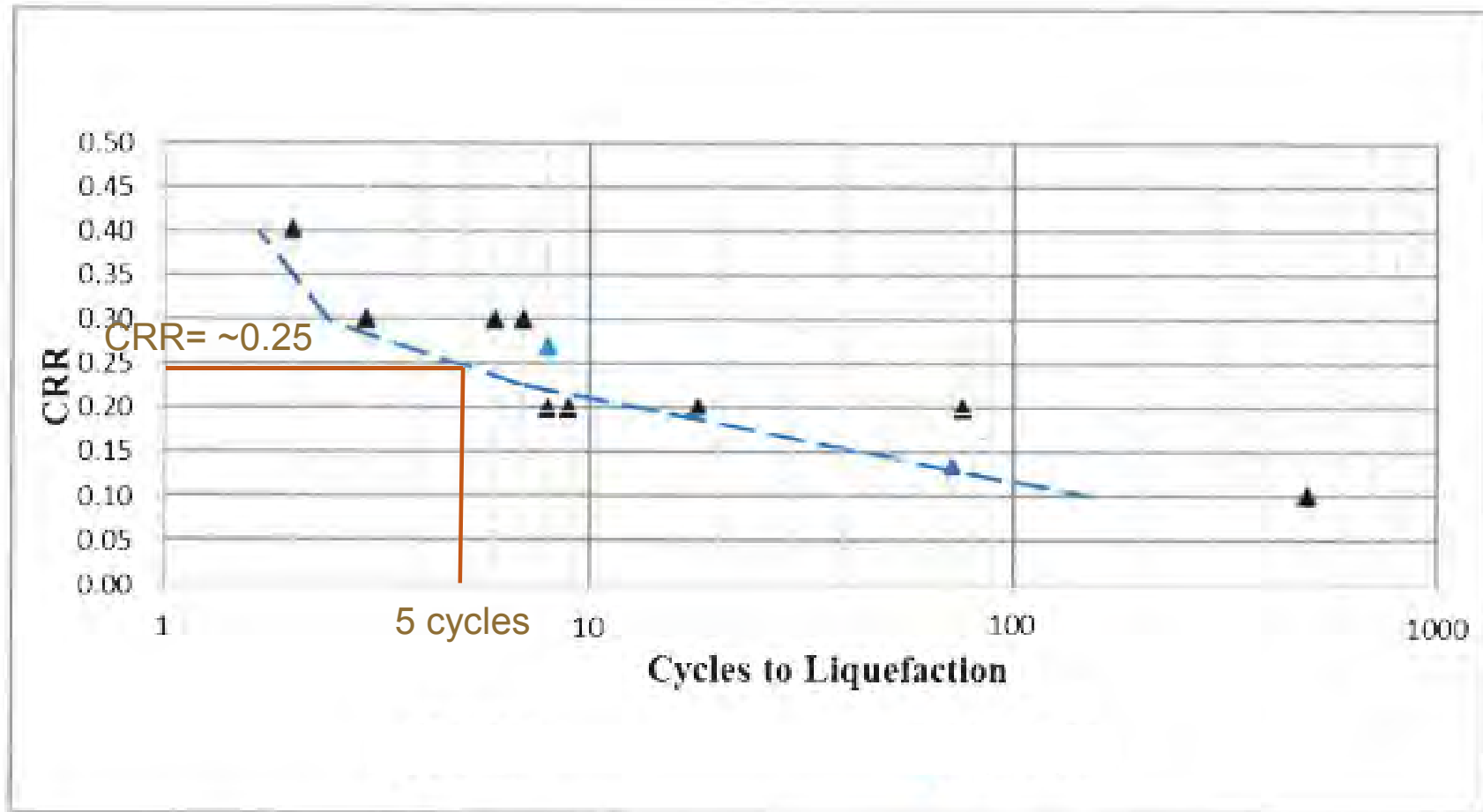


# Equivalent Uniform Cycles



Mean Number of Equivalent Uniform Cycles at reference Stress of 65% of the Peak Stress versus Earthquake Magnitude. (Seed and Idriss (1982) and Idriss (1999))

# Cyclic Triaxial Testing



Cyclic Resistance Ratio v. Cycles to Liquefaction

Amaya et.al (2013) "Evaluation of Liquefaction Potential at Fly Ash Storage Reservoirs"

# CCR Liquefaction Analyses – Factors of Safety

Bolanger and Idriss (2007), “Evaluation of Cyclic Softening in Silts and Clays,” Journal of Geotechnical and Geoenvironmental Engineering.”

The  $CRR_{M=7.5}$  for natural deposits of claylike fine-grained soils can then be estimated as

$$CRR_{M=7.5} = 0.96 \cdot 0.83 \frac{s_u}{\sigma'_{vc}} K_\alpha \quad (12)$$

$$CRR_{M=7.5} = 0.8 \frac{s_u}{\sigma'_{vc}} K_\alpha \quad (13)$$

$$CRR_{M=7.5} = 0.18 \cdot OCR^{0.8} \cdot K_\alpha \quad (16)$$

For tailing slimes, the above estimate of CRR should tentatively be reduced by about 20% as suggested by the data in Fig. 7(a). In

OCR = 1.6 to 4 (field to lab avg.)

$CRR_{M=7.5} = 0.24$  to  $0.49$

FS = 3.7 to 5.8

FS<sub>min</sub> (avg) = 4.8

$S_u/\sigma'_{vc}$  from CU = 0.4 to 0.81

$CRR_{M7.5} = 0.29$  to  $0.58$

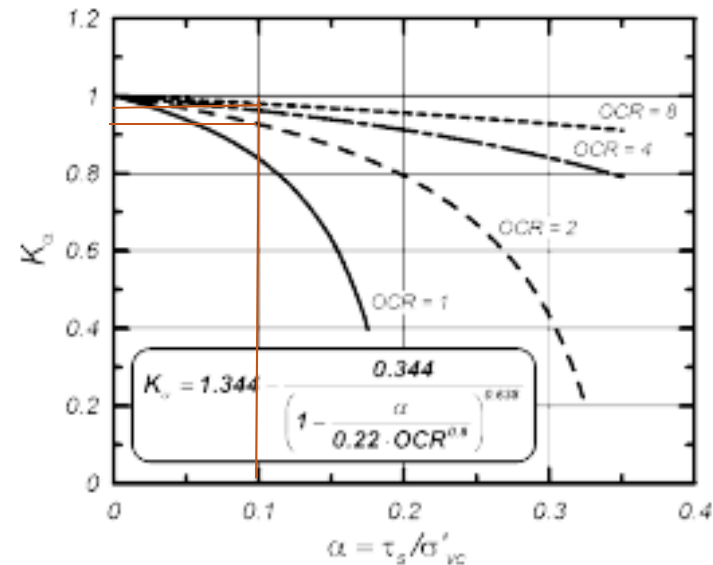


Fig. 6.  $K_\alpha$  versus  $\alpha$  for clay at various OCR

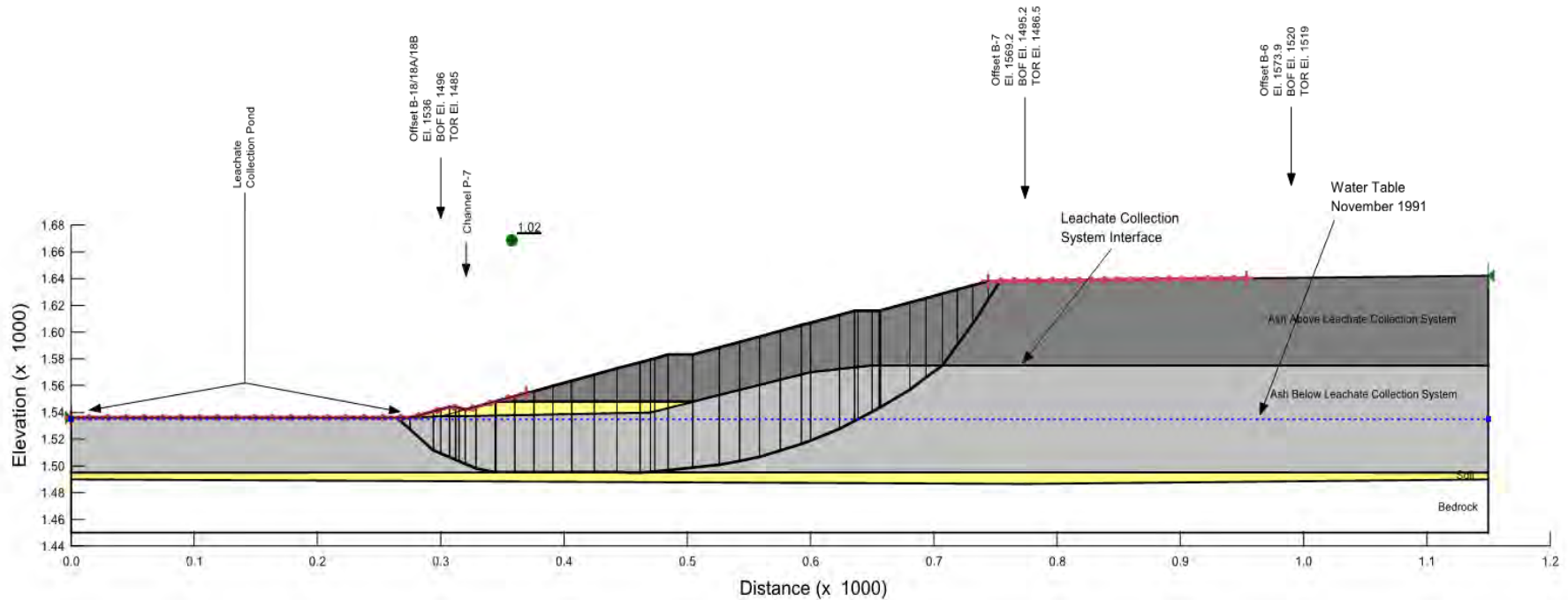
# Seismic Stability Analyses

ANALYSIS METHOD:  
Morgenstern-Price

2% Probability of Exceedance in 50 Years with SA 1.0 Second  
Horizontal Earthquake Coefficient: 0.07g

SOIL PROPERTIES:

Name: Native Soil Model: Undrained (Phi=0) Unit Weight: 130 pcf Cohesion: 4000 psf  
 Name: Ash Below LCS Model: S=f(overburden) Unit Weight: 81 pcf Tau/Sigma Ratio: 0.25 Minimum Strength: 1000  
 Name: Ash Above LCS Model: Mohr-Coulomb Unit Weight: 100 pcf Cohesion: 0 psf Phi: 30.7 °  
 Name: Bedrock Model: Bedrock (Impenetrable)  
 Name: Geonet/PVC Interface Model: Mohr-Coulomb Unit Weight: 1 pcf Cohesion: 0 psf Phi: 15 °



# Impoundment Closure Plan Evaluation Summary

- Goal is to develop a robust geotechnical investigation program
- Collect volume of field data and high quality undisturbed samples for:
  - Laboratory testing
  - Material characterization
- Perform engineering analyses to address
  - Stability
  - Settlement
  - Liquefaction
- Meet new CCR Rule requirements

# Impoundment Closure Plan Evaluation Summary

- Robust field and laboratory testing program provide:
  - Supporting data for realistic engineering properties;
  - Optimize static and seismic analyses;
  - Minimize uncertainty and risk;
  - Reduce regulatory review comments; and,
  - Well-designed impoundment closure plan.

# Questions



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